

# UNITED STATES AIR FORCE RESEARCH LABORATORY



## HOLOGRAPHICALLY FORMED POLYMER DISPERSED LIQUID CRYSTAL DISPLAY DEVICES: FABRICATION AND CHARACTERIZATION

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**FOR THE COMMANDER**



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Chief, Crew System Interface Division  
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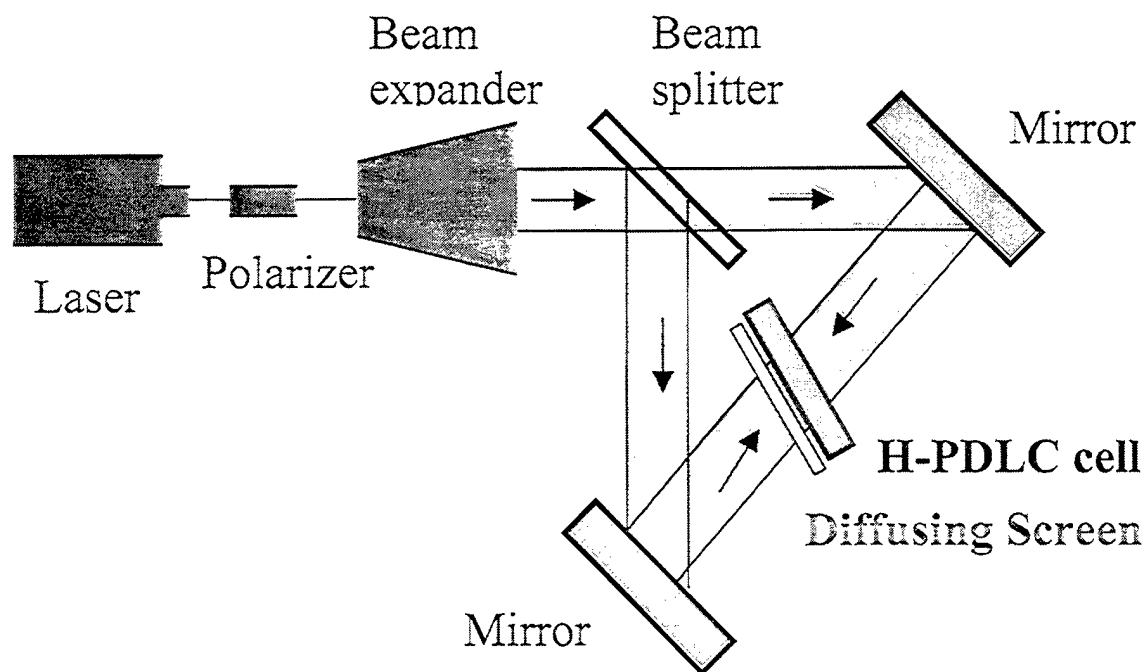
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## FOREWORD

This project, originally entitled "Reflective Display Prototype Fabrication," was performed as part of the Air Force Research Laboratory (AFRL) in-house HWIS<sup>1</sup> WU<sup>2</sup> 71841105 (formerly ASTARS<sup>3</sup> JON<sup>4</sup> 20030664 until 20 November 2000) by dpiX LLC of Palo Alto CA via the AFRL In-House Support Contract F33601-99-D-J001 with Raytheon (Raytheon Purchase Order Number G435143). This purchase order provided \$210,000 of DARPA High Definition Systems (HDS) support to dpiX LLC. The dpiX project spanned the period 1 July 1999 through 31 December 1999 and had a total project cost of \$369,073, of which dpiX provided a cost share of \$159,073 via an internal program. The government share of the funding, \$210,000 to dpiX plus \$18.4K for the Raytheon handling and subsequent in-house evaluations, was provided by DARPA HDS (PE62708E, FY1998) in the form of "AFRL In-House Support" to Dr. Darrel G. Hopper as DARPA Agent.

This report was assembled, formatted, and edited by Dr. Hopper of AFRL based on two reports from dpiX dated 30 November 1999 and 14 December 1999, and other dpiX material. A color or electronic version of this report is available upon request from AFRL/HECV, 2255 H Street, Building 248, Wright Patterson AFB OH 45433-7022.

The experimental setup for HPDLC device fabrication is illustrated below. Devices with extended viewing range employ a diffusing screen during the fabrication laser beam exposure.



<sup>1</sup> Human Systems Center Workunit Information System (HWIS)

<sup>2</sup> Workunit (WU)

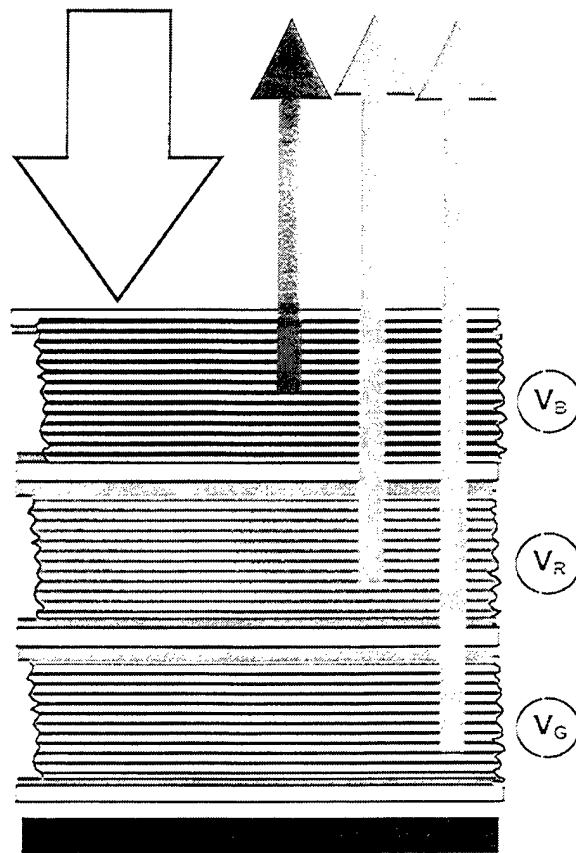
<sup>3</sup> A Science and Technology Activity Reporting System (ASTARS)

<sup>4</sup> Job Order Number (JON)

## PREFACE

The purpose of this AFRL In-House project was to fabricate and characterize reflective display sample devices based on HPDLC materials invented under a previous DARPA-funded, AFRL-managed extramural Cooperative Agreement F33615-96-2-1940 (see Reference 1). The earlier extramural effort paid to develop the technology but not for hardware deliverables. Under the presently reported in-house effort dpiX delivered and demonstrated ten samples to AFRL on 14 December 1999 and provided full technical support for evaluation at AFRL for three months (January-March 2000).

The ten samples all operate by reflecting ambient light. Two are full color with a vertical stack of three HPDLC layers as illustrated below. The other eight are monochrome red, green, or blue.



**Black absorbing background**

## ACKNOWLEDGEMENTS

We gratefully acknowledge the partial financial support from the Defense Advanced Research Projects Agency (DARPA) under the AFRL In-House Support Contract. We thank Dr. Darrel G. Hopper and Mr. Frederick M. Meyer of AFRL for their support throughout the project.

## 1. SUMMARY

Operating video rate, low power, reflective display devices samples were built and delivered. These devices were built in the holographically-formed polymer dispersed liquid crystal (HPDLC) fabrication facility established at dpiX based on the HPDLC technology developed under an earlier DARPA-funded, AFRL-managed project (see Reference 1).

The samples exploited the best materials sets identified by dpiX and its partner, Brown University. Materials development continued at dpiX in parallel with the proposed task with improvements identified incorporated into the delivered displays. The various sample devices were fabricated to enable evaluation of the status of HPDLC material to enable creation of a reflective display technology.

Two types of devices were provided.

The first type of devices was represented by operating numerical displays, one in the form of a functional digital clock and the other in the form of an uncommitted numerical display capable of being driven via a simple 5 V digital interface. This first type of device was intended to allow assessment of the application of HPDLC technology for simple information displays, but was not planned to be suitable for detailed electro-optical evaluation.

The second type of HPDLC device samples was specifically designed for detailed electro-optical evaluation and comprised eight simple single-pixel test cells with electrical contacts.

This report describes the ten samples and a full set of dpiX-measured data for each.

## **2. INTRODUCTION**

### **2.1 Specific Objectives**

The first objective was to build single pixel (50mm x 50mm) test cells with tuned reflected wavelengths. Cells were to be assembled using both the conventional<sup>5</sup> HPDLC material structure and the dpiX-proprietary integrated diffusing structure to broaden the viewing angle. The cells delivered were to be fully characterized at dpiX and the data provided.

The second objective was to build stacked single pixel cells consisting of optically coupled red, green and blue sub-cells, each independently driven. The sub-cells were to be matched to achieve a suitable reflected white point under typical illumination when they would be all in the reflective state. Again, versions were to be assembled using both conventional HPDLC structures and with integrated diffusing layers. The cells delivered to the Air Force DARPA Agent were to be fully characterized at dpiX and the data provided.

The third objective was to build two separate 4-digit, 7-segment HPDLC displays. These were to be integrated with suitable driver circuits in two configurations. The first segmented display was to include drivers and a commercial clock chip to realize a fully functional digital clock. The second segmented display configuration was to include the driver and interface circuits to allow the numerical display to be driven by the user through a simple 5 V interface in any desired fashion.

### **2.2 Samples**

There were ten HPLCD samples delivered by dpiX to the Air Force DARPA Agent as described below. The measurements and characterizations of these samples are provided in this report. These ten samples may be characterized as follows:

- One functional HPDLC clock display.
- One functional HPDLC numerical display with a simple 5 V interface and operating instructions.
- Six functional monochrome red, green, and blue (RGB) single pixel test cells suitable for full electro-optical evaluation (three standard, three diffuse). Full characterization details, including reflectance, transfer characteristics, and response times were measured.
- Two functional multi-color (stacked red, green, blue) test cells suitable for full electro-optical evaluation (one standard, two diffuse). Again, full characterization details were measured as for the monochrome samples.

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<sup>5</sup> Conventional HDPLC structures are also referred to, variously, as regular, standard, non-diffuse, or specular.

### 3. METHODOLOGY

#### 3.1 Fabrication Method

All of the HPDLC cells and displays were produced and characterized at the dpiX facilities in Palo Alto CA. Appropriate safety measures were observed for all chemical handling and laser exposure steps described below.

The fabrication procedure comprised some eleven steps as follows:

1. An HPDLC mixture of liquid crystal material, monomer, photo-initiator, and other constituents was prepared in the light-safe clean room.
2. Glass substrates with the desired patterns were cleaned and prepared.
3. Appropriately sized spacers were applied to one substrate (4  $\mu\text{m}$  to 10  $\mu\text{m}$ ); the substrates were then heat-treated to affix the spacers.
4. A precise amount of HPDLC material was applied to one substrate.
5. The cover glass was applied and the cell was vacuum-sealed.
6. The cell was transported to the laser exposure station in a light-safe box.
7. The sample was placed in position on the holography table and exposed for the appropriate amount of time; it is at this point, depending on the holography and sample set-up, that the color and diffusing power (if any) of the sample was determined.
8. The sample was exposed to the interfering laser beams and the HPDLC sample was produced.
9. The optional post-cure UV, or heat exposure, took place at this point.
10. Leads or pins were attached to the sample.
11. The sample was built into a clock display, a single cell display, or a stacked cell display, and characterized.

## **3.2 Characterization Protocol**

The ten samples were classified into five groups for electro-optical characterization. These classes and their testing protocols are as summarized in the following five subsections.

### **3.2.1 Clock Displays**

The testing procedure sequence for the segmented four-character clock and programmable displays was as follows:

1. Make sure all segments switch before packaging.
2. ELDIM EZContrast cross-section.
3. Diffuse spectral reflectance.
4. Diffuse photopic reflectance.

### **3.2.2 Single Pixel RGB Conventional (Specular)**

The testing procedure sequence for the conventional (specular) monochrome red, green, and blue test devices was as follows:

1. Specular reflectance and chromaticity (specular angle for HPDLC layer offset from substrate).
2. Peak reflectance vs. voltage.
3. Spectral Reflectance.
4. Response time.

### **3.2.3 Single Pixel RGB Diffuse**

The testing procedure sequence for the diffuse monochrome red, green, and blue test devices was as follows:

1. Diffuse spectral reflectance and chromaticity.
2. Peak reflectance vs. voltage.
3. Diffuse photopic reflectance.
4. ELDIM cross-section.
5. Response time.

### **3.2.4 Stacked RGB Conventional (Specular)**

The testing procedure sequence for the conventional (specular) stacked white device was as follows:

1. Specular reflectance for stacked cell (specular angle for HPDLC layers offset from substrate).
2. Chromaticity for red, green, blue, white, cyan, magenta, yellow, black (RGBWCMYK).

### **3.2.5 Stacked RGB Diffuse**

The testing procedure sequence for the diffuse test device was as follows:

1. Diffuse spectral reflectance for stacked cell.
2. Chromaticity for (RGBWCMYK).

### 3.3 Measurement Methods

#### 3.3.1 Diffuse Sample Reflectance

##### 3.3.1.1 Angular Width of Reflection Peaks for Diffuse Samples

A company called ELDIM (Reference 2) manufactures a so-called EZContrast measurement system which was used to acquire the angular width of the reflection peaks for the diffuse HPDLC samples. This system consists of a conoscopic optical head with a charge-coupled device (CCD) detector placed in relation to the optics such that each pixel on the CCD corresponds to light entering the optical head at a particular angle. With this system, light coming from the entire viewing cone of a display (out to 80°) can be captured in a matter of minutes. This computer-controlled device can measure both transmissive and reflective displays (with the appropriate options). With the reflection option, directional light can be introduced to the sample through beam-splitting optics in the measurement head.

In the dpiX measurements, the directional beam was generally incident at about 10° off normal. The reflected light was then collected and the resulting angular distribution analyzed.

##### 3.3.1.2 Angular and Spectral Reflectance Distribution Functions for Diffuse Samples

The angular spectral reflectance distribution functions of each diffuse HPDLC sample was measured using the modified Commission Internationale de l'Éclairage (CIE) recommended reflectance-factor measurement (see Reference 3).

The sample was illuminated by a collimated light source directed at about 10° off normal of the sample surface being measured. A Koehler Illuminator (KI-125) from Labsphere supplies the collimated light. It employed a 125 W tungsten-halogen bulb run by a precision regulated direct current (DC) constant current source (LPS-200-H). This broadband light source had a correlated color temperature of about 3200°K.

The diffusely reflected beam was detected using a spectroradiometer, namely the Photo Research model PR-704. The sample was mounted on a miniature goniometer and rotated so that the center of the diffusely reflected beam was incident on the lens of the PR-704 optical head, as illustrated in Figure 1.

The samples were made such that the beam reflecting off the diffuse HPDLC layers is not coincident with the specular beam from the front surface glass substrate of the sample.

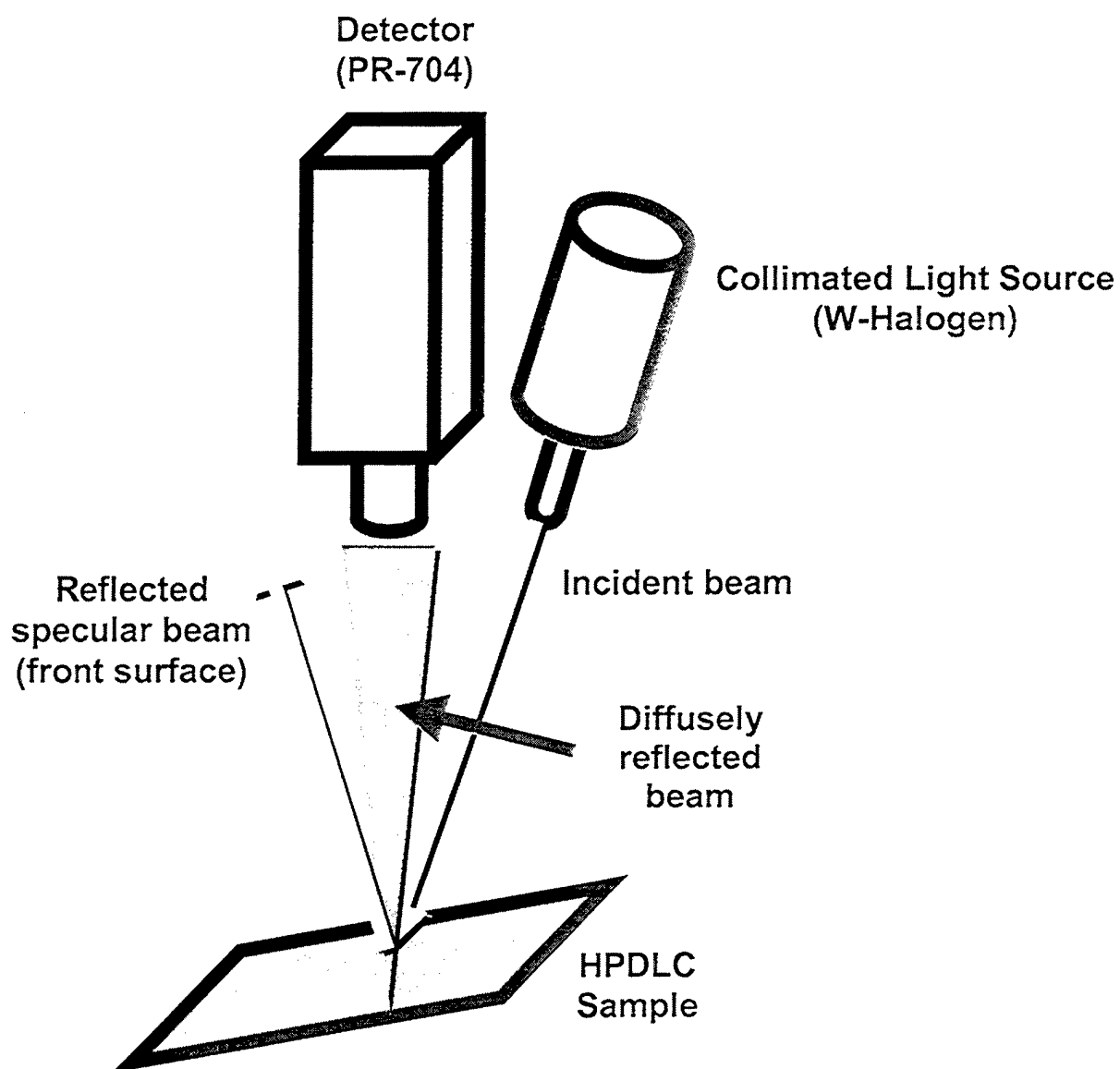
Two references were used. The first reference was a piece of diffusely reflecting metal foil with an approximately 15° diffusing angle.<sup>6</sup> This diffusing angle is roughly the same as that for the reflecting diffuser used in holographically forming the diffusing HPDLC layers.

The second reference was a white Lambertian diffuser,<sup>7</sup> which was used to provide a reference with no gain.

---

<sup>6</sup> The "diffusing angle" for such diffusers is that angle containing 90% of the reflected/transmitted light.

<sup>7</sup> A white Lambertian, or Lambertian, diffuser is a surface which perfectly diffuses incident light.



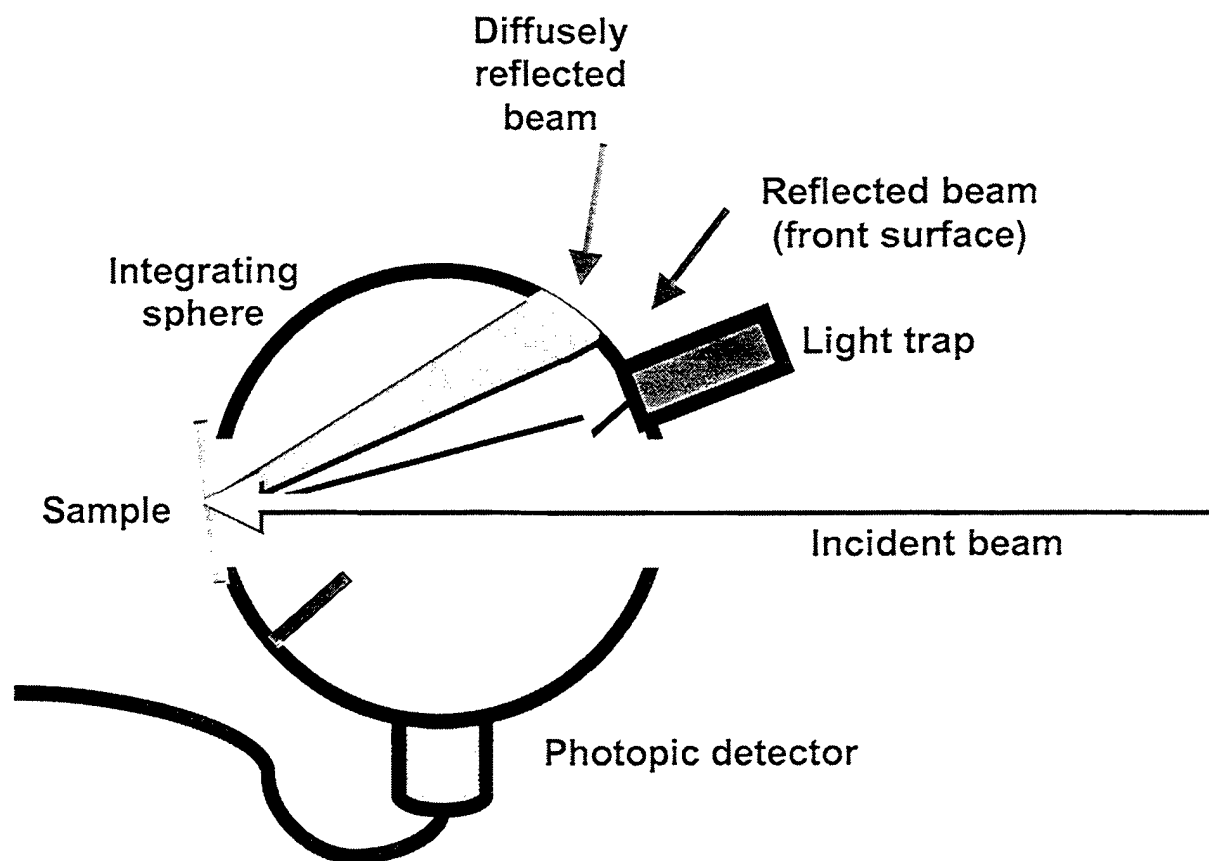
**Figure 1.** Schematic of the spectral reflectance measurement set-up for diffuse samples

### 3.3.1.3 Diffuse Photopic Reflectance

The diffuse photopic reflectance was obtained by using the collimated light source, an integrating sphere, and a photopic detector, as illustrated in Figure 2.

The sample was placed at one of the ports of the sphere and illuminated by the collimated light source such that the reflected specular beam from the front surface of the sample was directed into a light trap and removed from the measurement. The diffusely reflected beam from the HPDLC layer bounced off the reflective walls inside of the sphere and was detected by a photopic detector mounted on the sphere.

The reference for this measurement was, alternatively, a specular HPDLC sample or a white Lambertian diffuser.



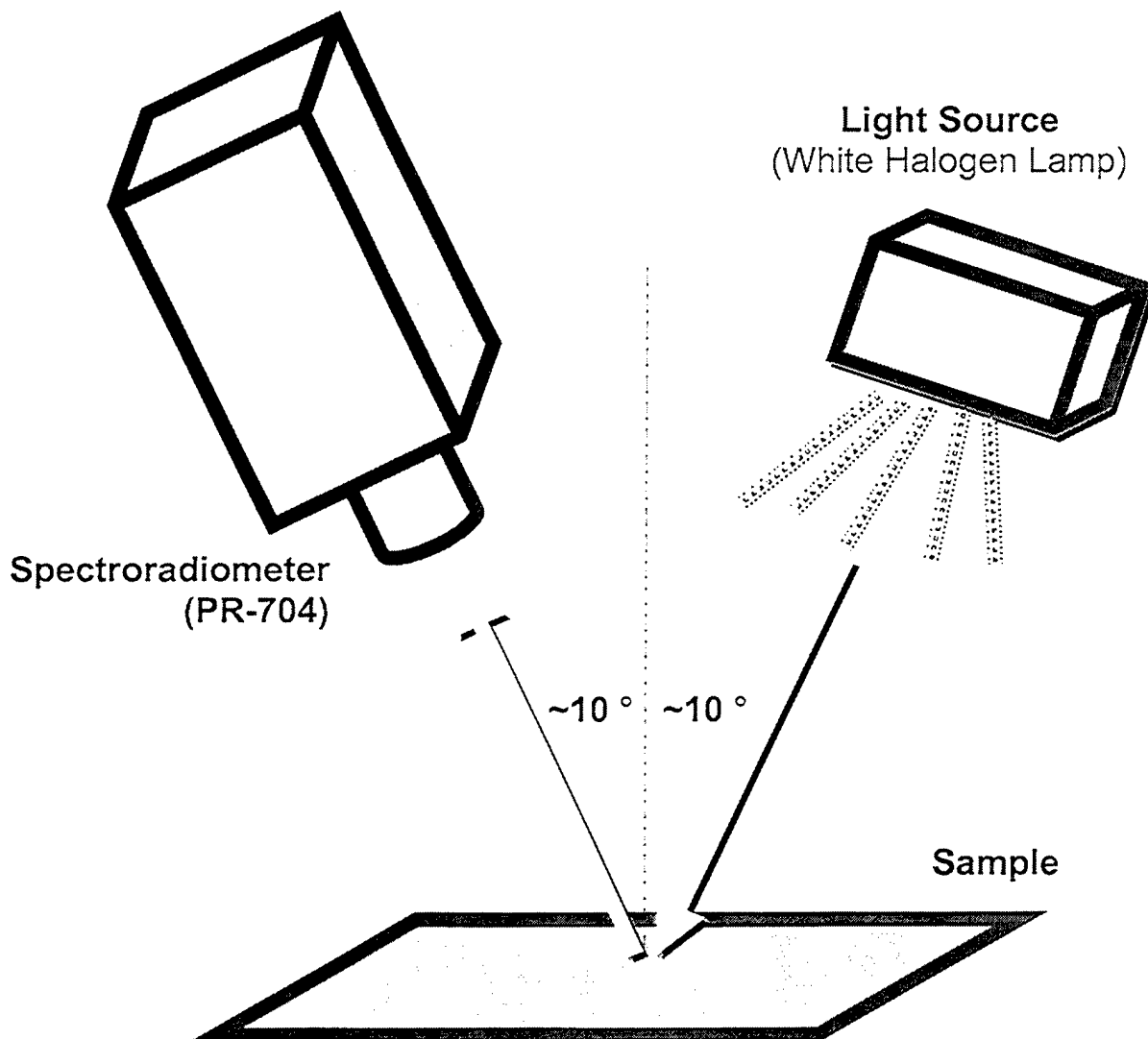
**Figure 2.** Schematic diagram showing how the diffuse photopic reflectance is measured.

### 3.3.2 Angular and Spectral Distribution Functions for the Conventional Samples

The reflectance measurements were performed as illustrated in Figure 3 for the regular, conventional (specular, non-diffuse) HPDLC cells. The sample was illuminated by a broadband Lambertian light source placed at about  $10^\circ$  off normal of the sample surface being measured. This source was a 2-in. integrating sphere from Labsphere with a 10 W tungsten-halogen bulb powered by the LPS-200-H (color temperature about 2800°K).

The specularly reflected beam was detected using the PR-704. The sample was mounted on a miniature goniometer and rotated so that the reflected beam from the HPDLC layer was incident on the lens of the PR-704 optical head. The reference was a coated front-surface mirror.

The samples were made such that the specular beam reflecting off the HPDLC layers was not coincident with the specular beam from the front glass surface of the sample.



**Figure 3.** Schematic diagram showing how the specular reflectance is measured.

### **3.3.3 Response Time**

The response time was measured with a set-up very similar to the diffuse spectral reflectance measurement. The major difference was that a silicon (Si) photodiode detector replaces the PR-704.

The signal was detected by an oscilloscope upon which the rise and fall times were observed.

The voltage signal applied to the samples for the time response measurement was a 1 kHz square wave modulated to turn off and on with a frequency of about 10 Hz.

The basic signal applied to the samples for static response measurements was a sine wave at 1.2 kHz with amplitude ranging from 0 V to 100-200 V.

## 4. RESULTS AND DISCUSSION

### 4.1 Characterization Results

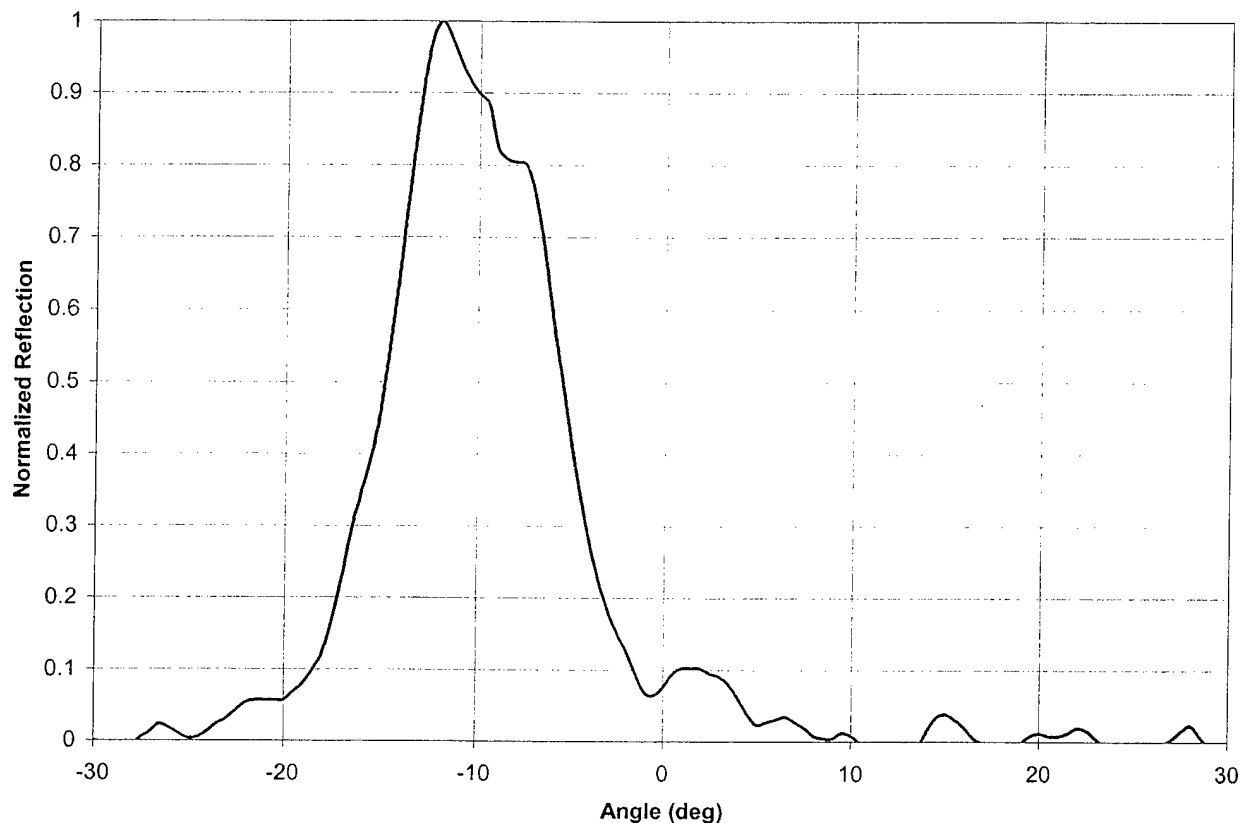
A list of presentations and publications reporting work accomplished under this DARPA-sponsored task in additional detail are provided in Appendices A and B.

We report here the characterization results for the measurements as specified in Characterization Protocol (page 4) and detailed in Measurement Methods (pages 6-9).

#### 4.1.1 Clock Display (Green Diffuse Character Segments)

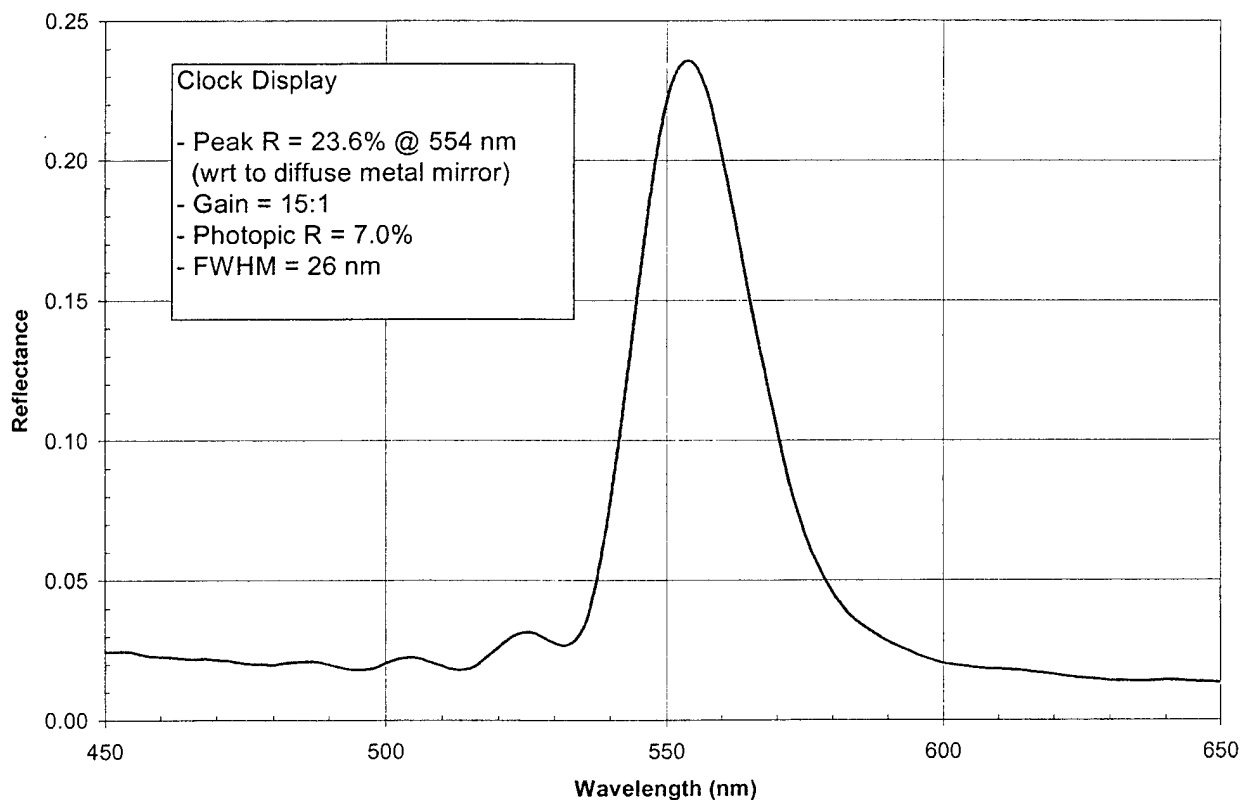
The clock display shows four digits with each comprising seven segments of green diffuse HPDLC material fabricated with both a  $10^\circ$  offset and a  $10^\circ$  diffuser. We include the results for both the clock display operating as an "up-timer" and the programmable display. All segments are operating for both displays as of the measurement and assembly date (30 November 1999).

Figure 4 illustrates the angular distribution of the reflection from the face of one of the display segments. The angular width, defined as the full-width-half-maximum (FWHM), of the sample is  $10^\circ$ , which is comparable to the diffuser used to form the device.



**Figure 4.** Angular distribution of the reflection from one of the clock display segments.

The diffuse photopic reflectance for the clock segment sample shown in Figure 4 is 8.8% with respect to a diffuse white (Lambertian) reference and 86.9% with respect to a specular green HPDLC reference. The other clock segments are similar, as illustrated in Figure 5.

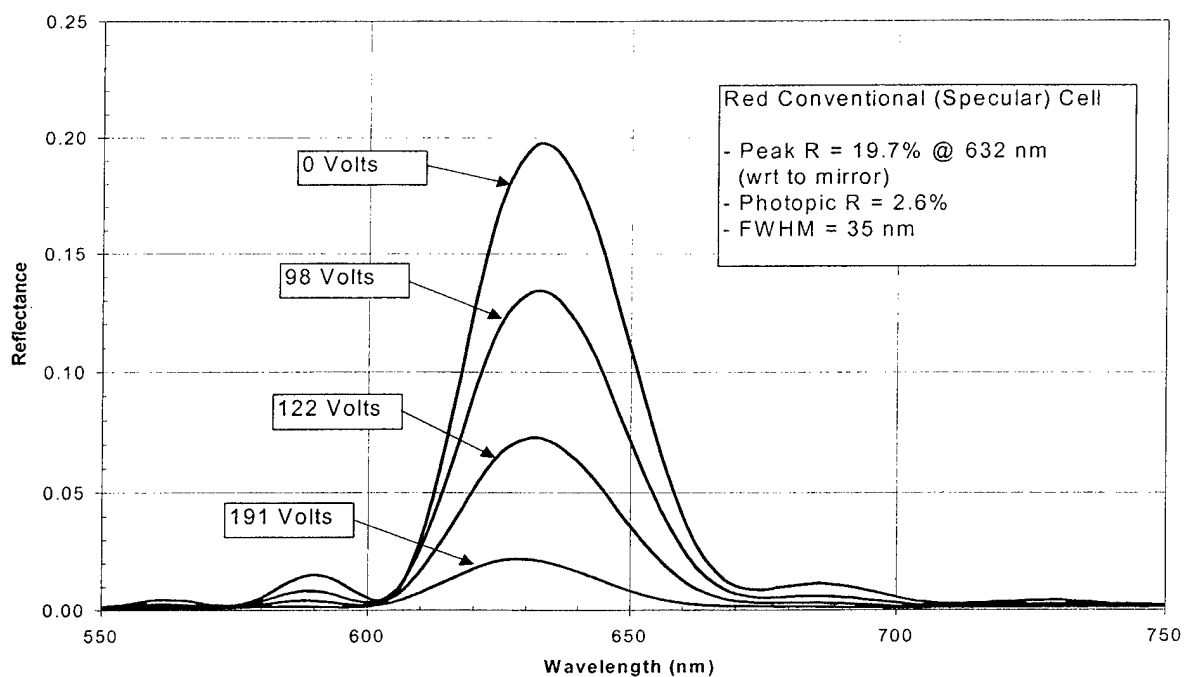


**Figure 5.** Diffuse spectral reflectance of a sample clock display segment.

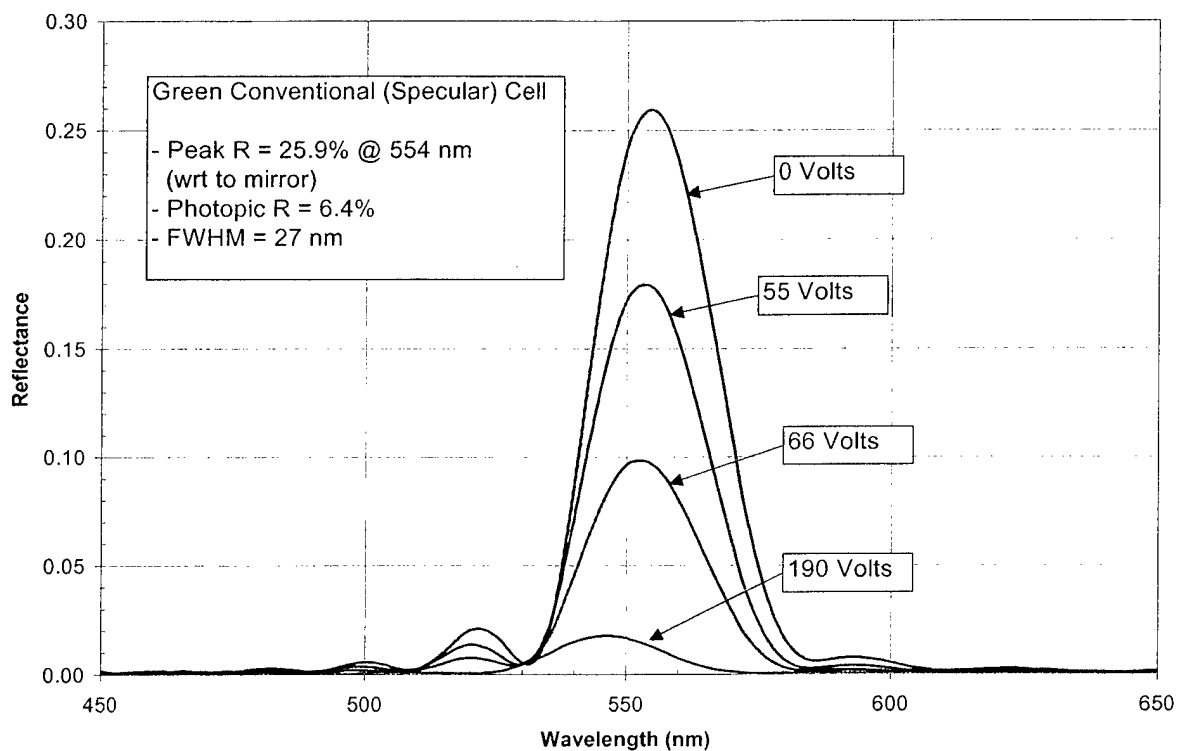
#### 4.1.2 Conventional (aka Specular) Monochrome Red, Green and Blue Samples

The monochromatic single color samples fabricated by the regular method have a  $10^\circ$  offset of the specular reflection direction of the HPDLC layer relative to the glass substrate specular reflection direction. However, a diffuser was not used. Thus, the angular distribution of the HPDLC reflection is very narrow (just slightly broadened relative to the glass specular reflection peak). These HPDLC samples are called variously, regular, normal, non-diffuse, or specular.

The spectral distributions measured for the regular (non-diffuse, or specular) samples fabricated to reflect red, green, and blue light are illustrated at four selected voltages (zero, 55-98, 66-122, and 190 V) in Figure 6, Figure 7, and Figure 8 respectively. An inset in each figure reports the measured peak reflectance and wavelength (at zero voltage with a mirror as reference), the photopic reflectance (white Lambertian reference), and the spectral FWHM in nanometers (nm).



**Figure 6.** Red conventional cell spectral reflectance at selected voltages.



**Figure 7.** Green regular conventional cell spectral reflectance at selected voltages.

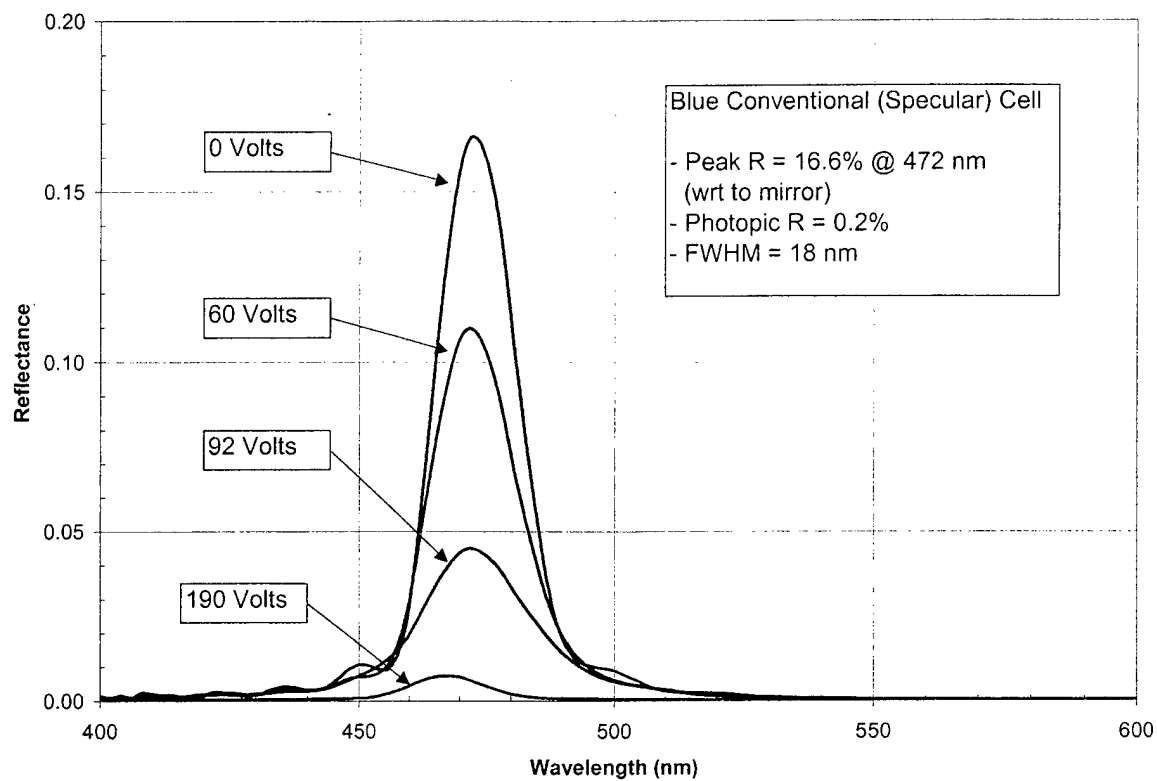


Figure 8. Blue conventional cell spectral reflectance at selected voltages.

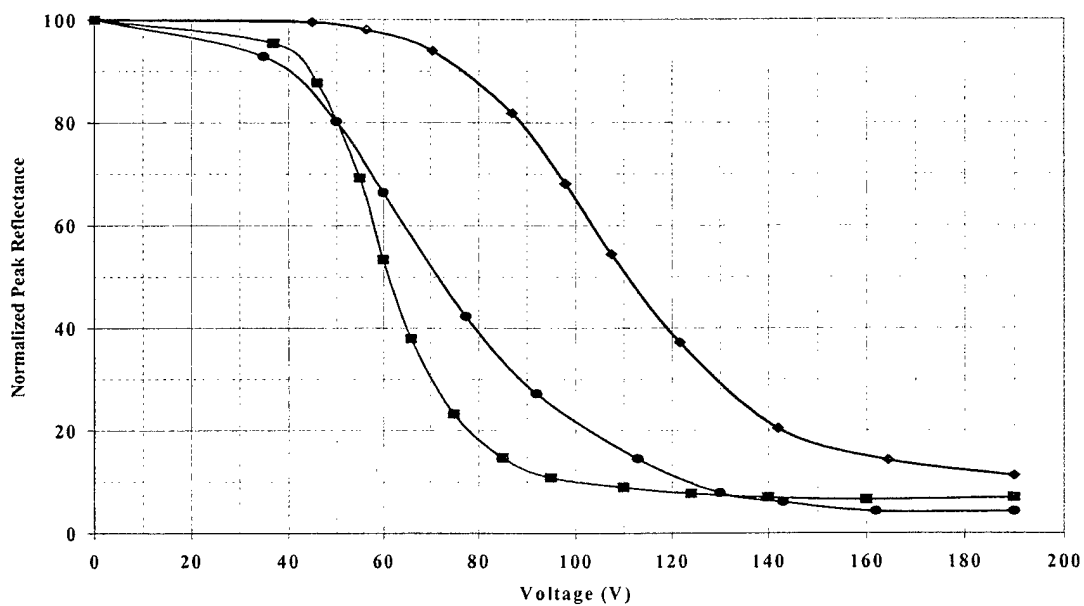


Figure 9. Red, green, and blue conventional cell peak reflectance vs. voltage.

The response time for the conventional (regular specular) cells are listed in Table 1.

The chromaticities (CIE 1976  $u'v'$ ) of the conventional (regular specular) cells are listed in Table 2.

**Table 1.** Response times for the conventional cells.

<b>Specular Cell</b>	<b>Max Driving Voltage</b>	<b>T<sub>on</sub> (bright to dark)</b>	<b>T<sub>off</sub> (dark to bright)</b>
Red	105 V	14.8 ms	0.6 ms
Green	95 V	1.9 ms	1.1 ms
Blue	75 V	12.1 ms	1.8 ms

**Table 2.** Chromaticities\* of the conventional cells.

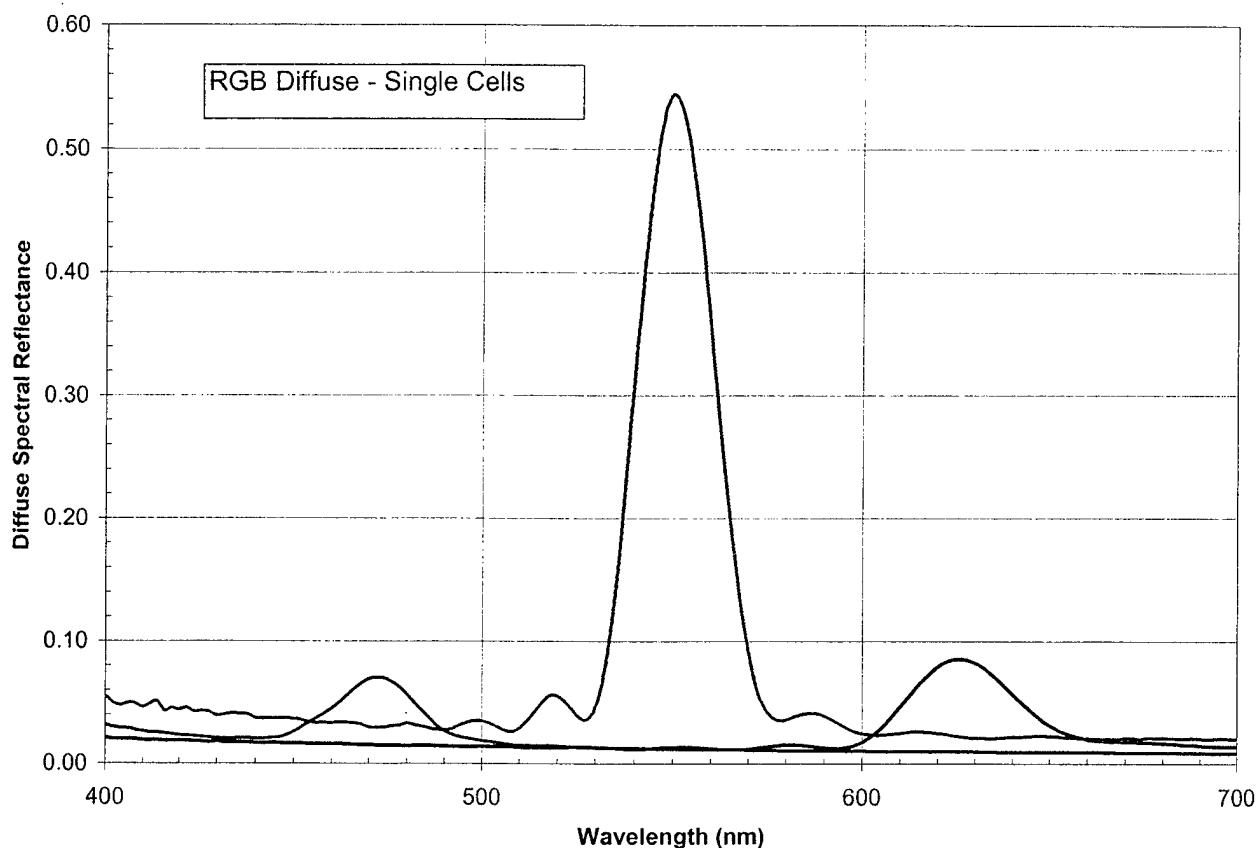
<b>Specular Cell</b>	<b>u'</b>	<b>v'</b>
Red	0.5153	0.5212
Green	0.1467	0.5761
Blue	0.1200	0.2491
Mirror	0.2592	0.5295

\* CIE 1976 ( $u',v'$ )

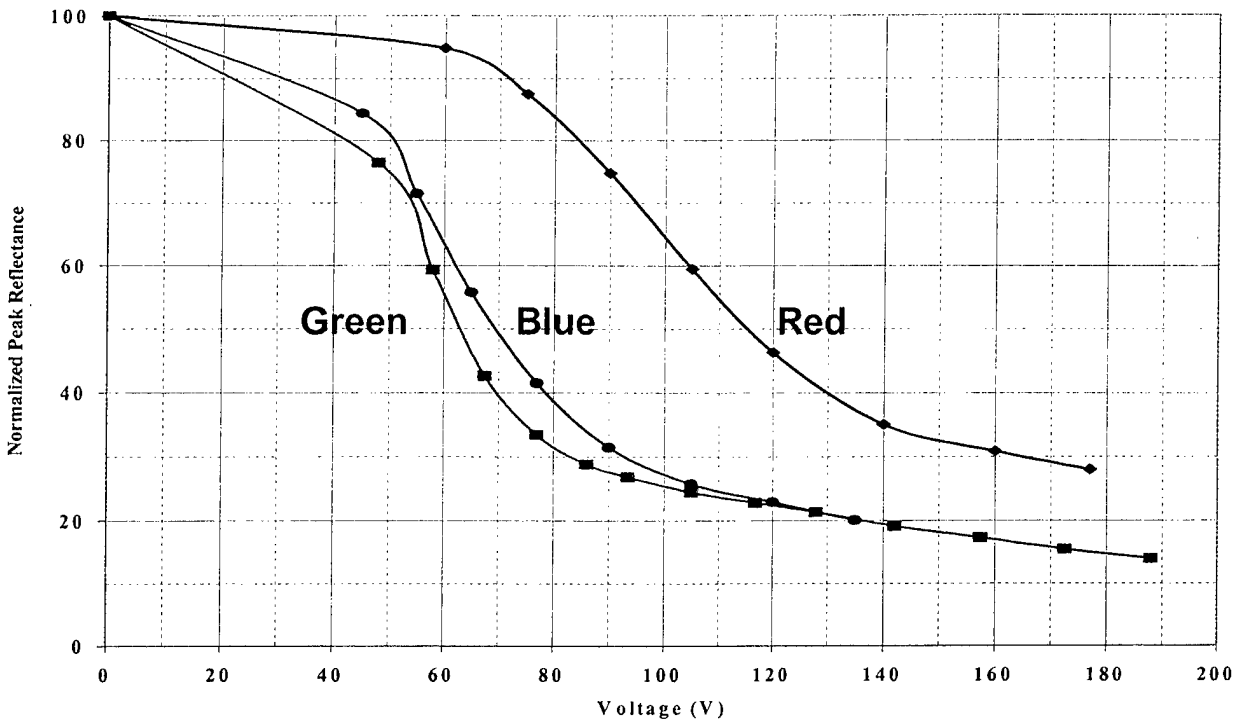
#### 4.1.3 Diffuse Monochrome (Red, Green, Blue) Single Cell Samples

The diffuse spectral reflectance distribution functions measured as a function of wavelength for the diffuse monochrome red, green, and blue single cell samples are plotted in Figure 10. Notice that the green reflectance is about eight times as efficient as either the blue or red.

The peak reflectance data measured as a function of voltage for the diffuse red, green, and blue HPDLC cells is illustrated in Figure 11.



**Figure 10.** Spectral reflectance of the diffuse red, green, and blue cells.



**Figure 11.** Peak reflection vs. voltage for the diffuse red, green, and blue HPDLC cells.

The photopic reflectances measured for the the red, green, and blue diffuse cells are summarized in Table 3. The first column of data is the photopic reflectance with respect to a white Lambertian diffuser. The second column of data is the photopic reflectance with respect to a specular sample of the same color.

The response times for the red, green, and blue monochrome diffuse cells are listed in Table 4.

The chromaticities (CIE 1976  $u'v'$ ) of the diffuse cells are listed in Table 5.

The angular distribution of the reflection from the face of one of the diffuse green cells is illustrated in Figure 12. The angular width (FWHM) of the sample is  $9^\circ$ , which is comparable to the  $10^\circ$  diffuser used to form the device.

**Table 3.** Photopic reflectance of the monochrome diffuse cells.

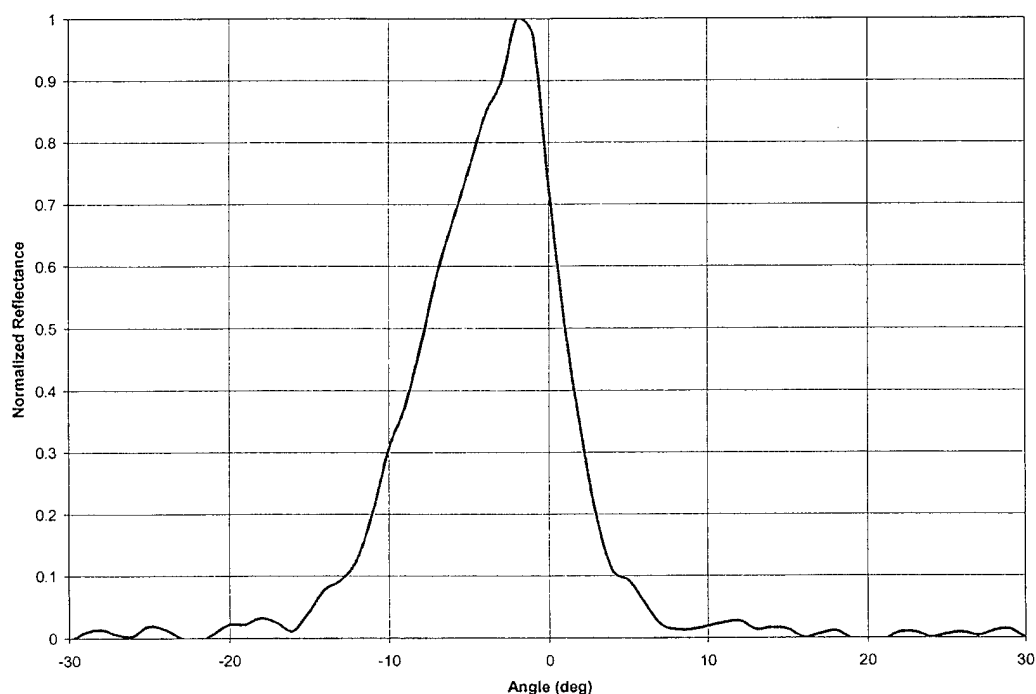
Cell	R% wrt white diffuser	R% wrt specular sample
Red	6.8	94.1
Green	8.4	76.4
Blue	1.9	95.4

**Table 4.** Response time for the monochrome diffuse cells.

Diffuse Cell	Max Driving Voltage	T <sub>on</sub> (bright to dark)	T <sub>off</sub> (dark to bright)
Red	106 V	2.8 ms	3.2 ms
Green	57 V	10.3 ms	8.0 ms
Blue	58 V	< 0.08 ms	11.3 ms

**Table 5.** Chromaticities of monochrome diffuse cells.

Diffuse Cell	u'	v'
Red	0.3584	0.5159
Green	0.1483	0.5661
Blue	0.2140	0.4644
Reference Diffuser	0.2511	0.5233

**Figure 12.** Angular distribution of the reflection from the diffuse green cell.

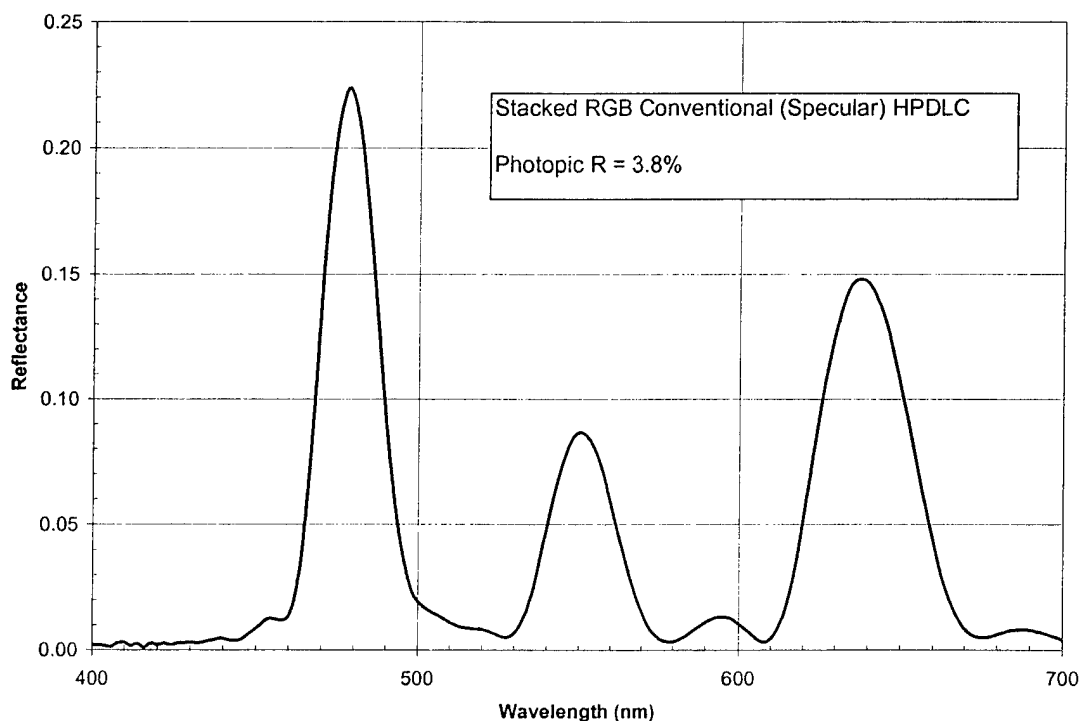
#### 4.1.4 White (Stacked Red, Green, Blue Layers) Single Cell Samples – Conventional

The stacked cells are constructed with the blue cell on the top of the stack, the red in the middle, and the green on the bottom. The blue cell is usually the least reflective and is given the top position to improve the color balance. The blue cell also has the most scattering or haze and therefore tends to wash out the colors for the entire stack.

The chromaticities measured for the eight various colors produced by the regular stacked white cell are listed in Table 6. The spectral reflectances are plotted in Figure 13.

**Table 6.** Chromaticity coordinates for conventional stacked white cell.

Specular Stacked Cell Color	u'	v'
Red	0.5101	0.5172
Green	0.1453	0.5753
Blue	0.1159	0.3574
White	0.2820	0.5133
Black	0.2606	0.4408
Cyan	0.1341	0.5221
Magenta	0.3906	0.4635
Yellow	0.2937	0.5414
Reference Diffuser	0.2599	0.5297



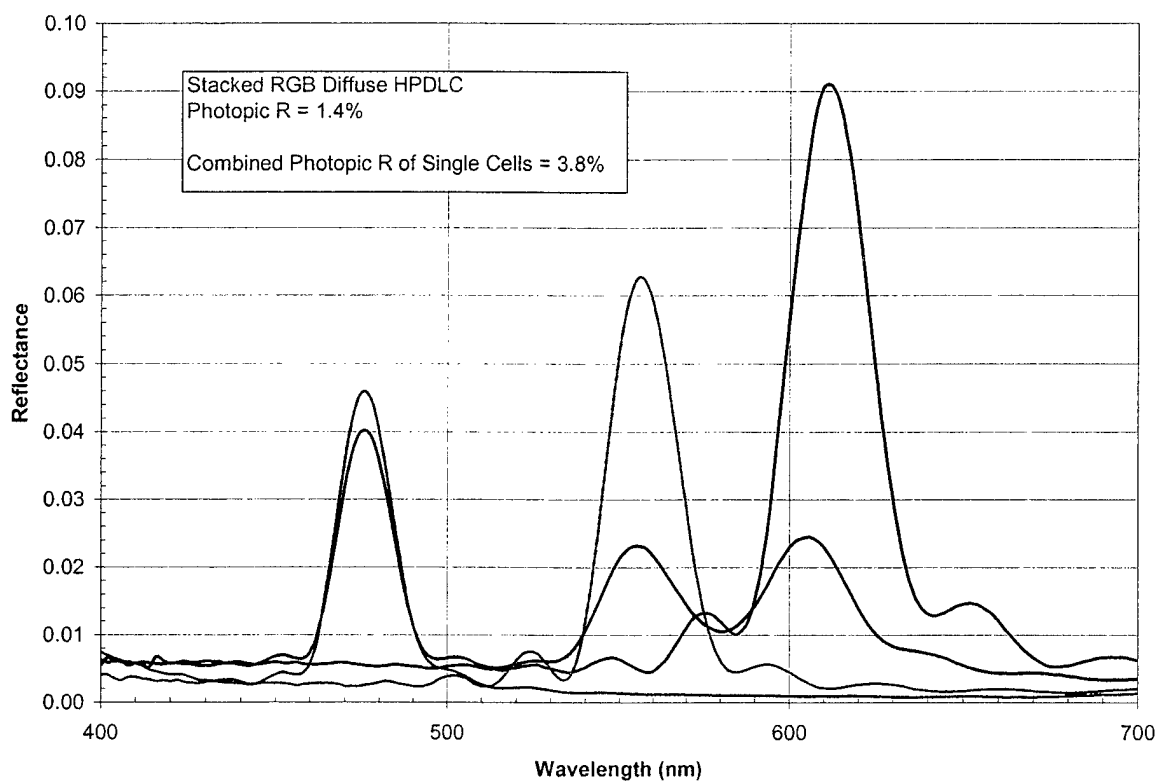
**Figure 13.** The spectral reflectance of the conventional stacked cell.

#### 4.1.5 White (Stacked Red, Green, Blue Layers) Single Cell Samples – Diffuse

The chromaticities of the diffuse stacked white cell are compared to the monochrome red, green, and blue diffuse cells in Table 7. The desaturation of the colors in the stacked cells is evident. The haze of individual cells also reduces the total reflectance of the stack as seen in Figure 14.

**Table 7.** Chromaticity coordinates for seven colors produced by white diffuse stacked cell.

Diffuse Stacked Cell Color	u'	v'	Single Diffuse Cell Color	u'	v'
Red	0.2982	0.5207	Red	0.4019	0.5280
Green	0.2042	0.5211	Green	0.1727	0.5659
Blue	0.2588	0.5061	Blue	0.1487	0.3857
White	0.2585	0.5232			
Cyan	0.2331	0.5175			
Magenta	0.2942	0.5105			
Yellow	0.2584	0.5374			
Reference Diffuser	0.2485	0.5216			



**Figure 14.** The spectral reflectance of the diffuse stacked cell. The line with the three low peaks is the stacked cell white state. The larger peaks at each color are for monochrome diffuse cells.

## 4.2 Operating Instructions

### 4.2.1 Clock Display

The 7-segment/4-digit clock display is operated by pushing the on/off switch at the back of the box to the “on” position. The clock display will begin counting up in a minutes:seconds format. The clock display may be stopped and restarted by alternately pushing the two buttons on the front of the display. To reset the reading, turn the clock display off and then on. This display takes two 9 V batteries. The batteries are accessible through the door at the back of the box.

### 4.2.2 Programmable Display

The 7-segment/4-digit programmable display requires the personal computer interface (PCI) digital input/output (I/O) card number PCI-6503 from National Instruments to be installed on a personal computer (PC) with an available PCI slot. The software to operate the programmable display was developed in LabView on a PC running Windows NT 4.0. It is recommended that a PC with the same operating system (OS) environment be used to operate the programmable display.

Follow the directions in the “DAQ Quick Start Guide” delivered with the display (Reference 4) to install the software drivers and documentation for the I/O card. In Step 3, install the PCI-6503 I/O card into an available PCI slot in the host computer. Please observe proper electrostatic safety procedures. Plug one end of the 50-pin ribbon cable into the connector on the I/O card. Plug the other end into the connector on the I/O connector block, CB-50LP. In Step 4 of the installation, make sure you select “PCI-6503” as the device, “CB-50” as the accessory (do not choose anything as the development platform). This will ensure that you have all the relevant documentation on-line. In Step 6 you will be directed to configure your device. In the “Devices and Interfaces” folder, double-click on the “PCI-6503 (Device 1)” folder. Double-click on one of the icons in the folder to configure the PCI-6503. Click on the “Accessory” tab. Choose “CB-50LP” for the accessory. Click the “Apply” button. Click on the “System” tab. Click on the “Test Resources” button and follow the directions on the screen. Click on the “Run Test Panels” button to test the I/O card. You should be able to measure 5 Vdc on the pin corresponding to the port and line turned on in the test panel (odd pins 1 through 47).

Connect the wires of the programming cable into connector pins of the CB-50LP as listed in Table 8. Make sure the wires are firmly held in place by tightening the screws on each pin.

**Table 8.** Map of pin labels to pin numbers for the programmable display.

Pin Label	Pin Number
C	1
L	5
D	3
G	2,4 or 6
H	7

Plug the other end of the programming cable into the connector on the back of the programmable display. Make sure that the key on the cable points toward the center of the display box.

Create a directory named "hpdlc" on the hard-drive of the PC (typically drive C:). Insert Disk 1 into the floppy drive of the computer and run the "Setup.exe" program. Change the installation directory to "C:\hpdlc". Proceed with the installation procedure by clicking on the "Finish" button.

Start the program by selecting Start>Programs>Hpdlc>HPDLCdrive.exe. Select the file "flatten.lsb" and click the "Open" button when prompted by the program.

Turn on the display by pushing switch to the "on" position at the back of the box. Select the segments that you want to turn on by clicking on them once with the mouse. The "colon" at the center of the display must be turned on for any of the other segments to work. When your selection is complete, press the "run" button (the right pointing arrow at the upper left of the program window). The segments you selected should now be turned on.

Note: the middle segment of the right-most digit does not work. If the contrast appears to be degraded, check the batteries.

#### **4.2.3 Single Pixel Monochrome Red, Green, or Blue HPDLC Cells – Conventional (Specular) and Diffuse**

There are two sets of wires coming from each cell. One set is one or more wires that includes a white wire. These are connected to one or more electrode stripes or symbols etched into one side of the cell. The other set is a single black wire connected to the common electrode on the other side of the cell. To operate a portion of a cell, hook up a voltage source between the single black common electrode wire and one or more wires from the other set.

The voltage source should be capable of supplying a 1 kHz sine or square wave with amplitude of up to 200 V.

We recommend that no more than a 50 V amplitude signal be applied at the outset of operation. Increase the amplitude to a maximum of no more than 200 V or until the contrast ratio reaches a maximum value, whichever comes first.

#### **4.2.4 Stacked Red, Green and Blue HPDLC Cells – Conventional (Specular) and Diffuse**

There are six wires coming out from each stack of cells – two for each cell. One wire from each cell is connected to the common electrode of that cell (labeled “red common”, etc.). The other wire is connected to one or more stripe electrodes on the other side of the cell (labeled “red stripes,” et cetera).

The same voltage source characteristics are required to operate these cells as in the single cell case. Please observe the same voltage restrictions as above.

To view a particular color on the stack, apply voltage to the cells as outlined in Table 9.

Intermediate colors may be displayed by applying differing voltages to the various cells in the stack.

**Table 9.** Logic map of color produced to the primaries commanded for the white cell samples.

<b>To view this color...</b>	<b>Turn on these cells.</b>
White	None
Red	Green and Blue
Green	Red and Blue
Blue	Red and Green
Cyan	Red
Magenta	Green
Yellow	Blue
Black	Red, Green and Blue

## 5. CONCLUSIONS

Display samples have been successfully fabricated and delivered for in-house studies at AFRL. Characterization studies at AFRL have begun (see Reference 5).

From the present dpiX report one can make several conclusions. Response times and switching field strengths were less than 12 ms and 29 V/ $\mu\text{m}$ , compared to the goals of 5 ms and 20 V/ $\mu\text{m}$ .

The dpiX HPDLC samples fabricated with a 10° diffuser in the one of the laser beams exhibited an viewing angle zone of 9-10° FWHM. Samples fabricated with the planes of laser beam interference offset 10° relative to the plane of the top glass substrate exhibited a 10° shift in their viewing angle zone. These two features will enable the fabrication of usable reflective displays.

The monochrome HPDLC devices exhibited switching speeds of that would easily support video rate operation. The  $T_{\text{on}}$  (bright to dark) times to reach 90% of commanded response for red, green, and blue were, respectively, 2.8, 10.3, and 0.08 ms. The  $T_{\text{off}}$  (dark to bright) times to reach 90% of commanded response for red, green, and blue were, respectively, 3.2, 8.0, and 11.3 ms. The maximum driving voltages (dark state) were 106, 57, and 58 V for red, green, and blue, respectively, in these timing experiments. The high drive voltage remains a concern.

The monochrome devices exhibited photopic reflectances relative to a white diffuser for red, green, and blue of 6.8, 8.4, and 1.9%, respectively, compared to the goal of 60% in each monochrome display. The stacked white photopic reflectance was 1.4% versus the goal of 50%.

Flexible displays should be possible using color HPDLC layers with thin and flexible plastic films as the HPDLC method integrates the display LC material into the plastic substrate. Thus, HPDLC materials may provide an excellent opportunity to develop a flexible display technology.

## 6. RECOMMENDATIONS

It is recommended that the samples prepared and characterized in this task be studied in-house at AFRL to verify the performance claimed and to ascertain the potential of HPLDC materials to support creation of a reflective display technology. The HPDLC material can also be used to fabricate other electro-optic devices for laser beam steering. It is recommended that the AFRL Materials and Manufacturing Directorate examine the samples for comparison with those from other contractors.

For display applications more work needs to be undertaken to increase the photopic reflectance through continued development of LC/monomer/initiator materials and stacked structures with offset Bragg wavelengths. The viewing angles need to be broadened further through the use of holographically-formed diffusing structures inside of the individual HPDLC layers. The HPDLC layers should be fabricated using linearly expanded laser beams and the moving substrate method to enable the making of large area displays. Web-based, roll-to-roll fabrication methods need to be developed along with transfer techniques to enable the successful stacking.

## 7. REFERENCES

1. Thomas F. Fiske, Jennifer Colegrove, Alan Lewis, Hanh Tran, Haiji Yuan, John Gunther, Gongjian Hu, Louis D. Silverstein, Gregory P. Crawford, L.-C. Chein, Chris Bowley, and Jack R. Kelly, *High Performance Paper White- and Full-Color Reflective Displays*, Technical Report Number AFRL-HE-WP-TR-2001-0099, 24 pp (June 2001). Available from Defense Technical Information Center, 8725 John J. Kingman Road, Suite 0944, Ft Belvoir VA 22060-6218.
2. ELDIM, 4, rue Alfred Kastler, 14000 CAEN – FRANCE, Phone: (33) 31 94 76 00, E-mail: [ELDIM@MSN.COM](mailto:ELDIM@MSN.COM).
3. G. Wyszecki and W. S. Stiles, *Color Science, Concepts and Methods, Quantitative Data and Formulae*, 2<sup>nd</sup> edition (Wiley, 1982), pages 155-156.
4. “DAQ Quick Start Guide,” (National Instruments, 1999), 12 pp., [www.natinst.com/support/](http://www.natinst.com/support/) .  
DAQ is a measurement ready data acquisition device.
5. Frederick M. Meyer and Darrel G. Hopper, “Holographically formed polymer dispersed liquid crystal sample characterization,” in *Cockpit Displays VIII: Displays for Defense Applications*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 4362, paper 21 (2001).

## 8. LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AC	Alternating current
AFRL	Air Force Research Laboratory
CCD	Charge-coupled device
CIE	Commission Internationale de l'Éclairage
CR	Contrast ratio
CRT	Cathode ray tube
DAQ	Data Acquisition device
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current
Diffuser angle	Angle which encompasses 90% of the light reflected/transmitted by a diffuser
ELDIM	ELDIM EZContrast system (performs optical Fourier transform on light leaving a surface to provide instantaneous measurement of angular distribution functions)
FWHM	Full-width at half-maximum
HDS	High Definition Systems
HPDLC	Holographically-formed polymer dispersed liquid crystal
I/O	Input/output
KI-125	Koehler Illuminator model KI-125 collimated light source
LC	Liquid crystal
LCD	Liquid crystal display
LPS-200-H	Labsphere model LPS-200-H precision regulated DC constant current source power supply
MRS	Materials Research Society
OS	Operating system
PC	Personal computer
PCI	Personal computer interface
PDA	Personal digital assistant
PDLC	Polymer dispersed liquid crystal
PR-704	Photo Research Model 704 spectroradiometer
RGB	Red, Green, Blue
RGBWCMYK	Red, Green, Blue, White, Cyan, Magenta, Yellow, black
SPIE	International Society for Optical Engineering (previously known as Society of Photo-Optical Instrumentation Engineers)
V	Volt
V90	Voltage that reduces reflectance to 10% of its initial value under zero voltage
W	Watt

## **APPENDIX A**

### **LIST OF PRESENTATIONS RELATED TO THIS DARPA-FUNDED TASK**

1. Improving the Voltage Response of Holographically formed Polymer Dispersed Liquid Crystals (H-PDLCs), C. C. Bowley at Optics of Liquid Crystals Conference, Puerto Rico, September 1999.
2. Drive-Voltage Reduction for HPDLC Displays, J. Colegrove, et al, IDW '99, Sendai, December 1999.
3. Electro-optic Investigations of H-PDLCs: The Effect of Monomer Functionality on Display Performance, SID 1999 International Symposium, San Jose, May 1999.
4. HPDLC Color Reflective Displays, H. Yuan, J. Colegrove, G. Hu, T. Fiske, A. Lewis, J. Gunther, L. Silverstein, C. Bowley, G. Crawford, L. Chien, and J. Kelly, SPIE Aerosense '99, April 1999.
5. Effect of Monomer Functionality on Performance of Holographically formed Polymer Dispersed Liquid Crystals, A. K. Fontecchio, C. C. Bowley, and G. P. Crawford, ECLC, Crete, April 1999.
6. Advances in Reflective Holographic Polymer-Dispersed Liquid Crystal Materials, MRS Spring Meeting, San Francisco, April 1999.
7. Holographically formed Polymer Dispersed Liquid Crystal Materials, MRS Graduate Student Award Presentation, San Francisco, April 1999.
8. Morphology of Holographically formed Polymer Dispersed Liquid Crystals, ILCC, Strasbourg, July 1998.
9. Holographically formed Liquid Crystal and Polymer Composites, ICCE, Las Vegas, July 1998.

## APPENDIX B

### LIST OF PUBLICATIONS RELATED TO THIS DARPA-FUNDED TASK

1. "Improving the Voltage Response of Holographically formed Polymer Dispersed Liquid Crystals (H-PDLCs)," submitted to *Molecular Crystals and Liquid Crystals*, C. C. Bowley, P. Kossyrev, S. Danworaphong, J. Colegrove, J. Kelly, T. Fiske, H. Yuan, and G. P. Crawford, (to be published).
2. "Drive-Voltage Reduction for HPDLC Displays," J. Colegrove, H. Yuan, T. Fiske, S.-T. Wu, J.R. Kelly, C. Bowley and G.P. Crawford, *Proceedings of the International Display Workshop(IDW'99)*, pp. 105-109 in Shendai, Japan (December1999).
3. "Electro-Optic Investigations of H-PDLCs: The Effect of Monomer Functionality on Display Performance," C. C. Bowley, A. K. Fontecchio, G. P. Crawford, and H. Yuan, *1999 SID International Symposium Digest of Technical Papers*, Volume XXX, 958-961 (1999).
4. "HPDLC color reflective displays," H. Yuan, J. Colegrove, G. Hu, T. Fiske, A. Lewis, J. Gunther, L. Silverstein, C. Bowley, G. Crawford, L. Chien, and J. Kelly, in *Cockpit Displays VI: Displays for Defense Applications*, Proceedings of SPIE, Volume 3690, pp. 196-216 (1999).
5. "Reflection from dual-domains in a holographically formed polymer-dispersed liquid crystal material," Chris C. Bowley, Gregory P. Crawford, and H. Yuan, *Appl. Phys. Lett.*, Volume 74, Number 21, pp. 3096-3098 (1999).
6. "Effect of Monomer Functionality on Performance of Holographically formed Polymer Dispersed Liquid Crystals," A. K. Fontecchio, C. C. Bowley, and G. P. Crawford, *Molecular Crystals and Liquid Crystals* (1999).
7. "Advances in Holographic Polymer Dispersed Liquid Crystal Technology," C. C. Bowley, A. K. Fontecchio, J. J. Lin, H. Yuan, and G. P. Crawford, *MRS Symposium Proceedings*, p. 559 (1999).
8. "High Efficiency Color Reflective Displays with Extended Viewing Angle," H. Yuan, G. Hu, T. Fiske, A. Lewis, J. E. Gunther, L. D. Silverstein, C. Bowley, G. P. Crawford, L.-C.Chien, and J. R. Kelly, *Proceedings of the 18th International Display Research Conference*, p. 1135 (1998).
9. "Dual-domain Reflection from Holographically formed PDLCs," C. C. Bowley, H. Yuan, and G. P. Crawford, *Proceedings of the 18th International Display Research Conference*, p. 851 (1998).
10. "Morphology of Holographically formed Polymer Dispersed Liquid Crystals (H-PDLC)," Chris C. Bowley, Haiji Yuan, and Gregory P. Crawford, *Molecular Crystals and Liquid Crystals* (1998).

## APPENDIX C

### PROGRAMMING RULES FOR THE PROGRAMMABLE DISPLAY MEMO FROM LC TECHNOLOGIES, INC.

Nov. 8, 1999

Merrill M. Groom  
LC Technologies, Inc.  
P.O. Box 366  
Kent, Ohio 44240  
330-325-7094  
mgroom@lctechnologies.com

Dr. Tom Fiske  
dpiX LLC  
3406 Hillview Ave.  
Palo Alto, CA 94304-1345

Ph: 650-842-9665, Fax: 650-842-9793

Tom,

The following is a little info on the display demo drivers.

The long cable with 10 pin connector and loose wires at the other is for "direct drive" via your National digital interface card.

The pin labeled "C" connects to the Micrel 8031 clock input.

The pin labeled "L" connects to the Micrel 8031 latch input.

The pin labeled "D" connects to the Micrel 8031 data input.

The pin labeled "G" connects to the Micrel 8031 ground pin.

The pin labeled "H" connects to a FET switch that operates the control pin of the PICO high voltage inverter. With the "H" pin disconnected or held high (+5v), the output of the HV inverter will be zero. To turn on the high voltage, take this pin low (ground). This may help save the batteries when the unit is not being used but the operator forgets to shut off the power switch at the back of the unit.

When downloading data directly to the demo unit from the National card, remember to shift 31 data bits to the unit, take the latch pin high and then shift in the last (32<sup>nd</sup>) data bit. Shift LSB out first. The sequence follows:

- 1) present the data bit at "D"
- 2) take the clock "C" high then low
- 3) do this 31 times
- 4) present the 32nd data bit
- 5) take the latch "L" high
- 6) take the clock "C" high then low
- 7) take the latch "L" low

Note the direction that the programming cable and direct drive cable connect to the demo unit. The keying slot points toward the center of the unit. When operating the unit with the covers removed remember to orient the connector with the key toward the center of the box.

The unit will operate from one battery but two should double the operating period and help prevent the unit from "locking up" when first turned on.

The two little buttons on top are inoperable on units without the microprocessor installed.

The programming cable will be used if you would like to download code to the micro from your computer.

The code is a flavor of BASIC which the 'BASIC Stamp II' micro interpreter understands. It is free from Parallax, Inc at [www.parallaxinc.com](http://www.parallaxinc.com).

An additional unit, minus the HV inverter and with a STN cell, was built for hardware and software development. Two refinements may be to 1) use a thinner box and 2) be able to operate a unit directly from a laptop computer using something like DOS quick basic and the computer's serial (RS232) port.

When installing the displays, use the 20 pin extension headers to get the display closer to the front cover of the box. It is very difficult to insert the display's flimsy flat pins directly into a strip of 20 round pin sockets.

Best results for mounting and dismounting a display were to use the flat pin header (cut apart 24-pin DIP socket) directly on the display. Then, plug the display / flat pin header assembly into the single-in-line round pin header and then onto the demo unit. Always use the display with flat pin header attached. Always push on or pry off the display from the flat pin header. Never push or pry directly on the display or its pins.

\*\*\*\*\*

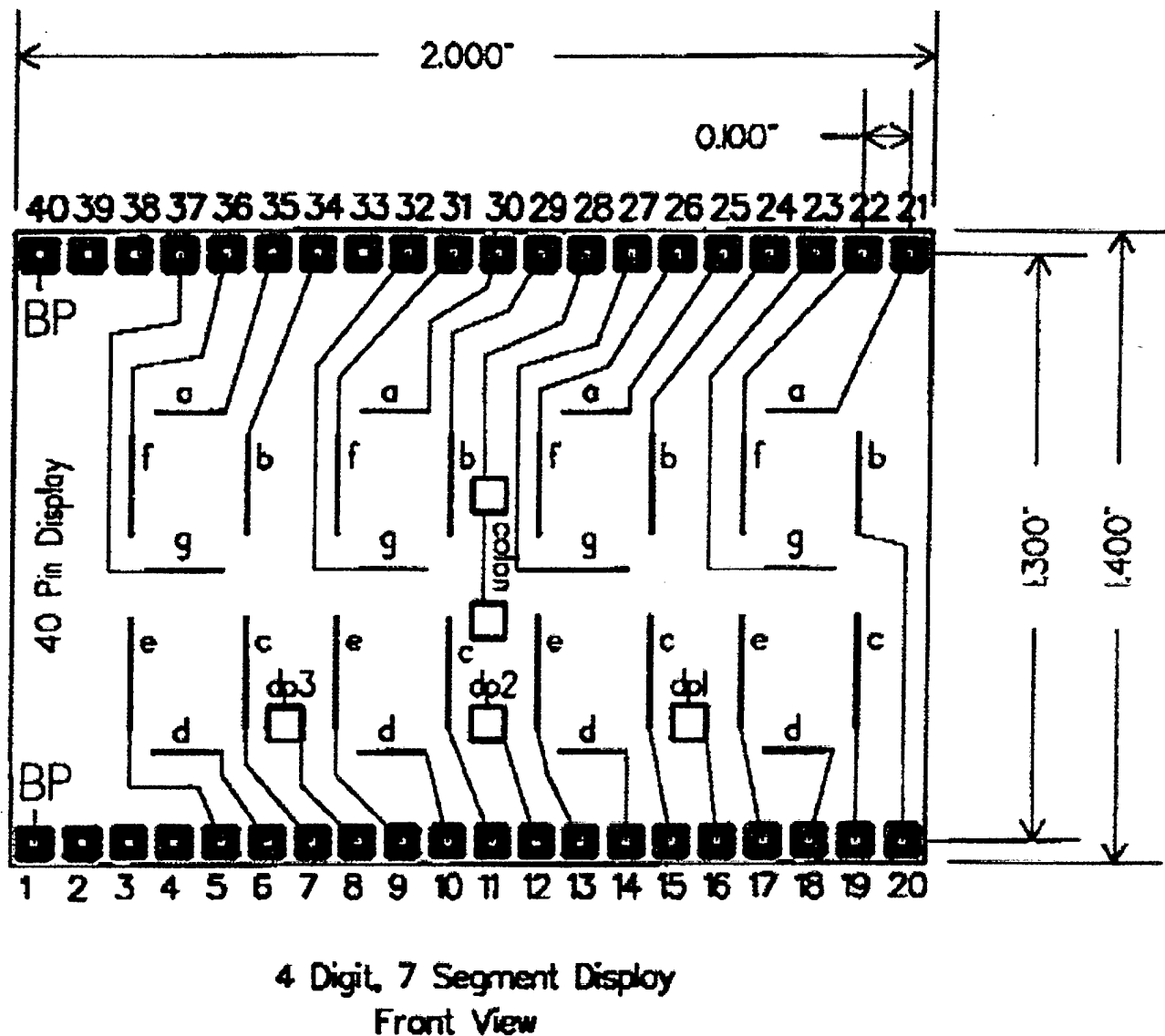
Date: Wed, 10 Nov 1999 12:05:10 -0500  
To: fiske@dpix.com  
From: Merrill Groom <mgroom@lci.kent.edu>

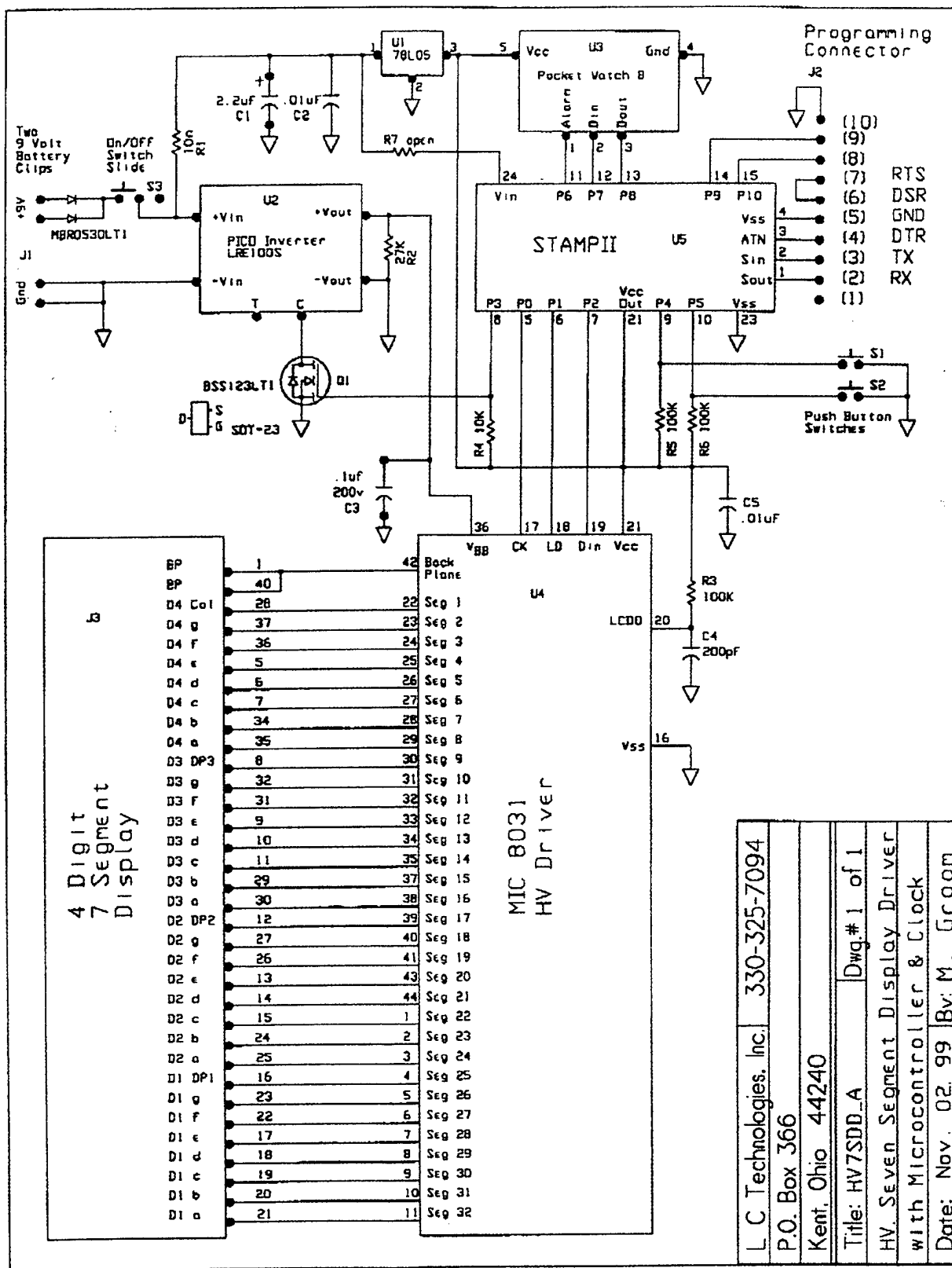
Tom,  
Just an additional note about the display drivers.  
For most reliable operation, when you are about to turn on the HV inverter via the HVOFF control line, load the driver chip with 0s (all segments off) then bring up the HV power.  
Merrill

## APPENDIX D

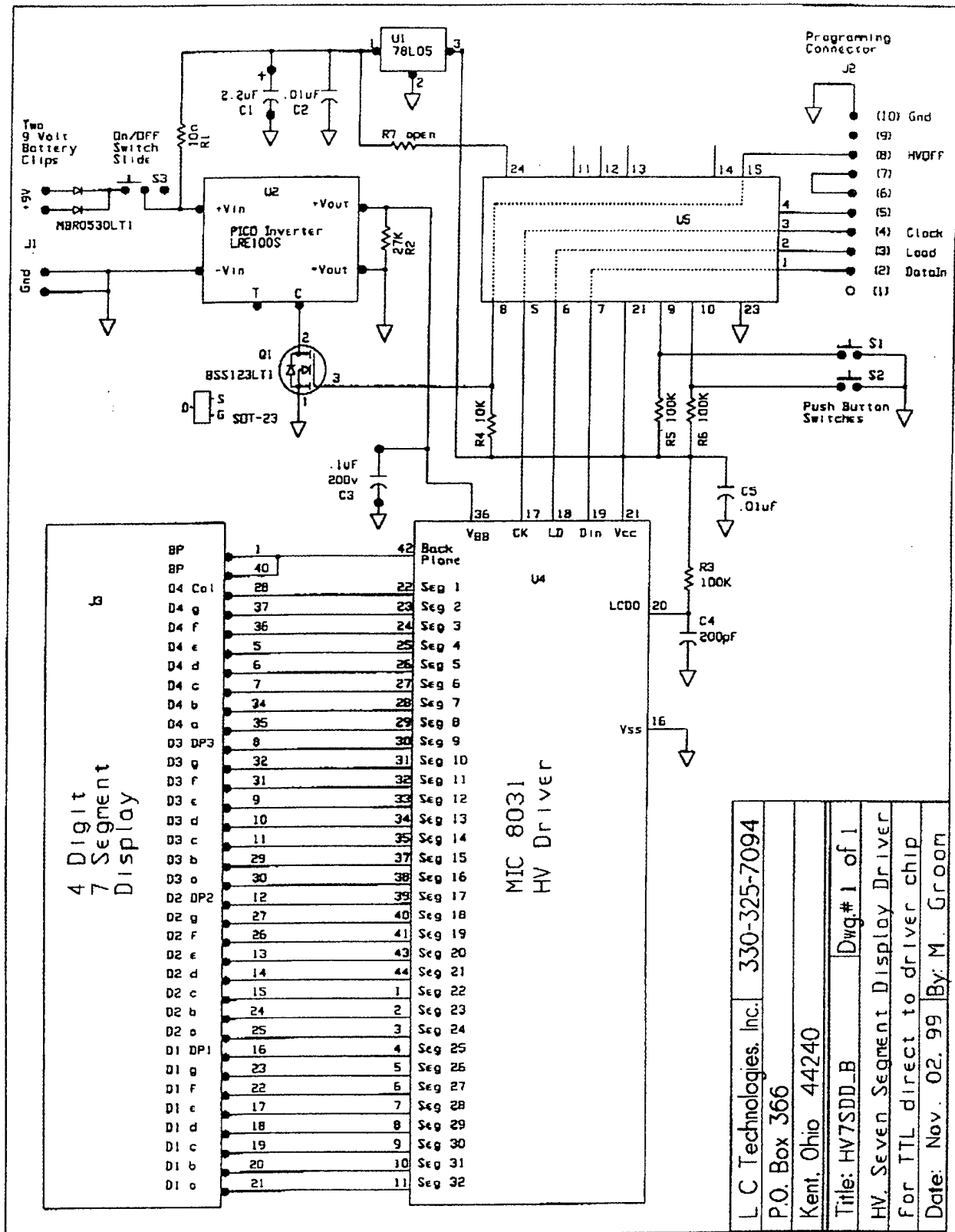
### SCHEMATIC DIAGRAMS FOR THE CLOCK AND PROGRAMMABLE DISPLAYS

The three schematic diagrams for the two segmented display, one clock and one programmable) are reproduced in this appendix in the form provided by LC Technologies, Inc., the dpiX subcontractor for drive electronics.





L C Technologies, Inc. 330-325-7094  
P.O. Box 366  
Kent, Ohio 44240  
Title: HV7SDD\_A Dwg.# 1 of 1  
HV Seven Segment Display Driver  
with Microcontroller & Clock  
Date: Nov. 02, 99 By: M. Groom



## APPENDIX E

### MICREL DRIVER CHIP SPECIFICATION

Specification for the Micrel driver chip used in the programmable HPDLC display delivered by dpiX under the current task. The chip is no longer available. Micrel contact information: <http://www.micrel.com/product-info/products/mic8030.html>, <http://www.micrel.com/contact/contact.shtml>, and phone (408) 944-0800.



### MIC8030

#### High-Voltage Display Driver

#### General Description

The MIC8030 is a CMOS high voltage liquid crystal display driver. Up to 38 segments can be driven from four CMOS level inputs (CLOCK, DATA IN, LOAD and CHIP SELECT). The MIC8030 is rated at 50V. Data is loaded serially into a shift register, and transferred to latches which hold the data until new data is received.

The backplane can be driven from external source, or the internal oscillator can be used. If the internal oscillator is used, the frequency of the backplane will be determined by an external resistor and capacitor. The oscillator need not be used if a DC output is desired.

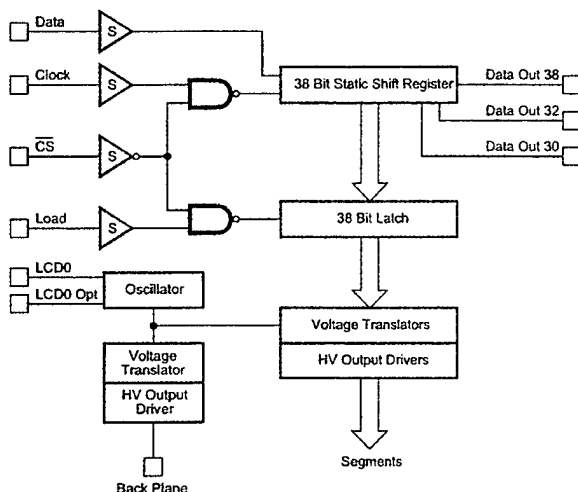
#### Features

- High Voltage Outputs capable of driving up to 100 volt outputs from 5 to 15 volt logic
- Drives 30, 32, or 38 segments
- Cascadable
- On chip Oscillator or External Backplane Input
- CMOS construction for wide supply range and low power consumption
- Schmitt Triggers on all inputs
- CMOS, PMOS, and NMOS compatible

#### Applications

- Dichroic and Standard Liquid Crystal Displays
- Flat Panel Displays
- Print Head Drives
- Vacuum Fluorescent Displays

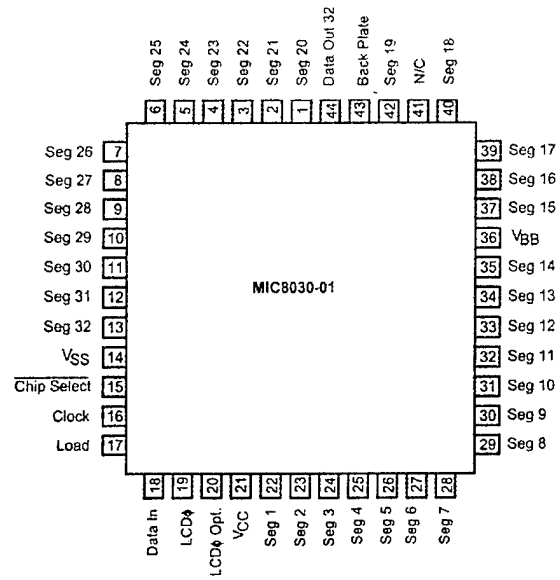
#### Functional Diagram



#### Ordering Information

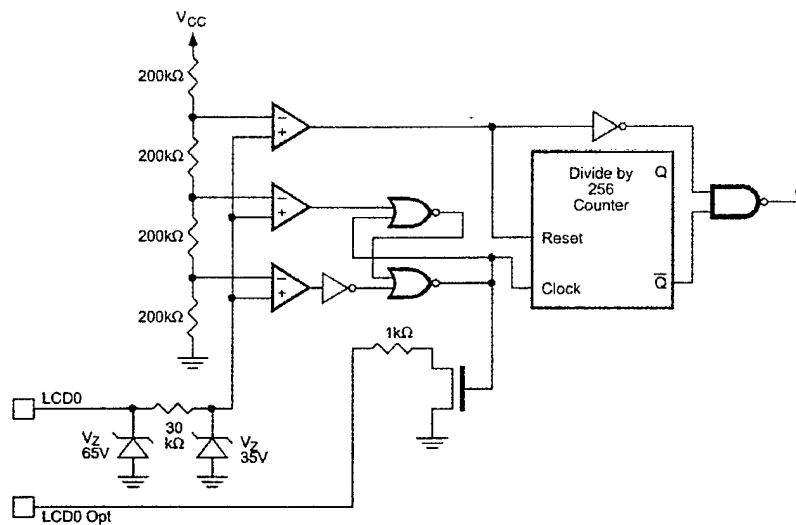
Part Number	Temperature Range	Package
MIC8030-01CV	0°C to +70°C	44-pin PLCC

## Pin Configuration



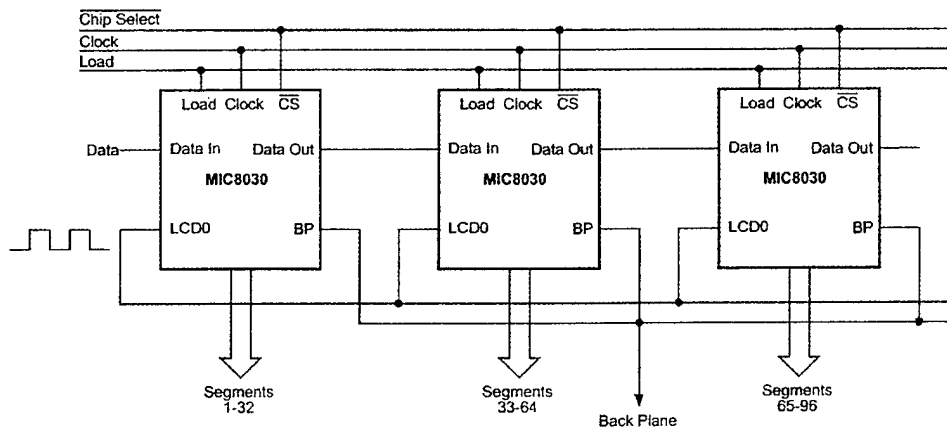
**44-Pin PLCC (-V)**

## Internal Oscillator Circuit

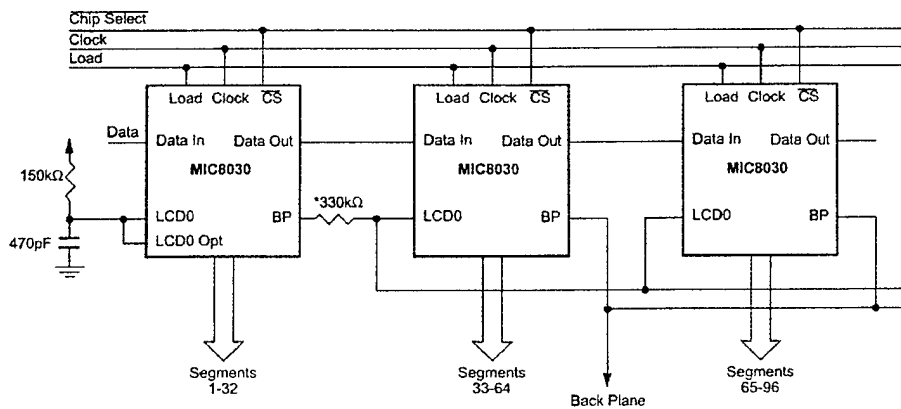


## Typical Application

### External Oscillator



### Internal Oscillator



\*Required if using MIC8031 with  $V_{BB} > 50V$ .

**Absolute Maximum Ratings**

V <sub>CC</sub>	18V
V <sub>BB</sub> (MIC8030)	75V
Inputs (CLK, DATA IN, LOAD, $\overline{\text{CS}}$ )	-0.5V to 18V
Inputs (LCD0)	-0.5V to 50V
Storage Temperature	-65°C to +150°C
Operating Temperature	-55°C to +125°C
Maximum Current into and out of any segment	20 mA
Maximum Power Dissipation, any segment	50 mW
Maximum Total power dissipation	600 mW

**DC Electrical Characteristics:** V<sub>CC</sub> = 5V, V<sub>SS</sub> = 0V, V<sub>BB</sub> = 50V, -55°C ≤ T<sub>A</sub> ≤ +125°C, unless otherwise noted.

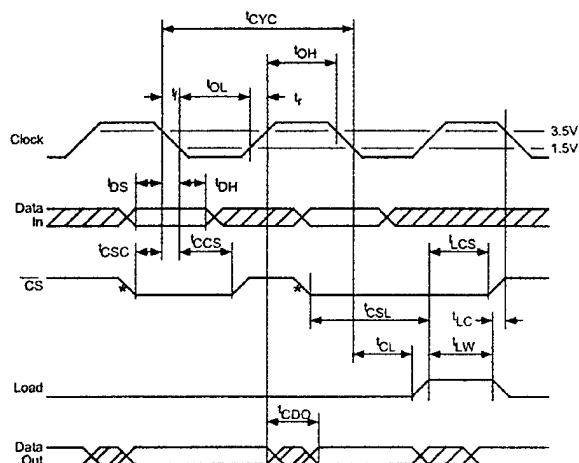
Symbol	Parameter	Condition	Min	Typ	Max	Units
<b>Power Supply</b>						
V <sub>CC</sub>	Logic Supply Voltage		4.5	5	5.5	V
V <sub>BB</sub>	Display Supply Voltage		20	35	50	V
I <sub>CC</sub>	Supply Current (external oscillator)	Note 1		35	250	μA
	Supply Current (internal oscillator)	Note 1		35	250	μA
I <sub>BB</sub>	Display Driver Current	f <sub>BP</sub> = 100Hz, no loads		7	100	μA
<b>Inputs (CLK, DATA IN, LOAD, <math>\overline{\text{CS}}</math>)</b>						
V <sub>IH</sub>	Input High Level		V <sub>CC</sub> -1.5	V <sub>CC</sub> -1.8	V <sub>CC</sub>	V
V <sub>IL</sub>	Input Low Level		0	2.5	2.0	V
I <sub>L</sub>	Input Leakage Current			<1	5	μA
C <sub>I</sub>	Input Capacitance	Note 2		5	10	pF
<b>Input LCD0</b>						
V <sub>IH</sub>	LCD0 Input High Level	Externally driven	0.9V <sub>CC</sub>	V <sub>CC</sub>	50	V
V <sub>IL</sub>	LCD0 Input Low Level	Externally driven	-0.5V	0	0.1V <sub>CC</sub>	V
I <sub>LCD0</sub>	LCD0 Leakage Current	V <sub>LCD0</sub> = 15V		2	10	μA
I <sub>LCD0</sub>	LCD0 Leakage Current	V <sub>LCD0</sub> = 35V		6	100	μA
I <sub>LCD0</sub>	LCD0 Leakage Current	V <sub>LCD0</sub> = 50V			1	mA
<b>Capacitance Loads (typical)</b>						
C <sub>LSEG</sub>	Segment Output	f <sub>BP</sub> < 100Hz			100	pF
C <sub>LBP</sub>	Backplane Output	f <sub>BP</sub> < 100Hz			4000	pF
V <sub>OAVG</sub>	DC Bias (Average) Any Segment	f <sub>BP</sub> < 100Hz, Note 2			+25	mV
<b>Output to Backplane</b>						
R <sub>SEG</sub>	Segment Output Impedance	I <sub>L</sub> = 100μA		1.4	10	kΩ
R <sub>BP</sub>	Backplane Output Impedance	I <sub>L</sub> = 100μA		170	312	Ω
R <sub>DATA OUT</sub>	Data Out Output Impedance	I <sub>L</sub> = 100μA		1.8	3	kΩ

Note 1: CMOS input levels. No loads.

Note 2: Guaranteed by design but not tested on a production basis.

**AC Electrical Characteristics:**  $V_{CC} = 5V$ ,  $V_{SS} = 0V$ ,  $V_{BB} = 50V$ ,  $-55^{\circ}C \leq T_A \leq +125^{\circ}C$ 

Symbol	Parameter	Min	Typ	Max	Units
$t_{CYC}$	Cycle Time	500			ns
$t_{OL}, t_{OH}$	Clock Pulse Width low/high	250			ns
$t_r, t_f$	Clock rise/fall			1	$\mu s$
$t_{DS}$	Data In Setup	100			ns
$t_{CSC}$	$\overline{CS}$ Setup to Clock	100			ns
$t_{DH}$	Data Hold	10			ns
$t_{CCS}$	$\overline{CS}$ Hold	220			ns
$t_{CL}$	Load Pulse Setup	250			ns
$t_{LCS}$	$\overline{CS}$ Hold (rising load to rising $\overline{CS}$ )	200			ns
$t_{LW}$	Load Pulse Width	300			ns
$t_{LC}$	Load Pulse Delay (falling load to falling clock)	0			ns
$t_{CDO}$	Data Out Valid from Clock			220	ns
$t_{CSL}$	$\overline{CS}$ Setup to LOAD	0			ns
$F_{BP}$	Backplane Frequency	50	100	2000	Hz

**Timing Diagram**

\* The  $\overline{CS}$  high-to-low transition will generate a clock pulse.

**Logic Truth Table**

Data In	Clock	Chip Select	Load	$Q_1(SR)$	$Q_N(SR)$	$Q_N(DRIVER)$
X	X	1	X	NC	NC	$Q_N(L)$
0	↑	0	0	NC	NC	$Q_N(L)$
0	↑	0	1	NC	NC	$Q_N(L)$
0	↓	0	0	0	$Q_N - 1 \rightarrow Q_N$	$Q_N(L)$
0	↓	0	1	0	$Q_N - 1 \rightarrow Q_N$	$Q_N(SR)$
1	↑	0	0	NC	NC	$Q_N(L)$
1	↑	0	1	NC	NC	$Q_N(L)$
1	↓	0	0	1	$Q_N - 1 \rightarrow Q_N$	$Q_N(L)$
1	↓	0	1	1	$Q_N - 1 \rightarrow Q_N$	$Q_N(SR)$

↑ = Rising Edge, ↓ = Falling Edge